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STORMWATER MANAGEMENT WITHIN GREENWICH BAY RHODE ISLAND

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STORMWATER MANAGEMENT WITHIN GREENWICH BAY RHODE ISLAND

BY

VINCENT DEINGENIIS

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE

REQUIREMENTS FOR THE DEGREE OF

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OF

VINCENT DEINGENIIS

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ABSTRACT

Stormwater runoff from municipalities bordering Greenwich Bay degrades the water quality and potentially the health of stakeholders. Monitoring bay water and effluent from sewage treatment plants is used to identify where management efforts need to be directed. Hypoxic water conditions and high concentrations of fecal coliform are the most pressing issues within Greenwich Bay. Observed concentrations of fecal coliform in shallow embayment's within the northern reaches of Greenwich Bay are often unsafe for the consumption of shellfish and unsafe for primary contact through swimming. Regional precipitation and discharge from a major river through statistical analysis suggest that the likelihood of hypoxic conditions in the bay is related to nutrients supplied during periods of high precipitation. These findings indicate that future management efforts should be directed toward incentivizing the tie-in of personal septic systems into municipal wastewater infrastructure, and the management of coastal land to prevent nutrient flux through stormwater runoff.

ACKNOWLEDGMENTS

Words cannot express my gratitude to my major professor for his invaluable time and energy spent as my mentor. Professor Burroughs spent countless hours giving feedback and comments on my writing through this entire process and I would not have been able to do this without him. I would also like to thank my defense committee for believing in me and inspiring me to think about my topic in a variety of different ways. I am so grateful for the insight and expertise given to me by my supervisor and co-workers. Their motivation and guidance through this process was invaluable to me. I would also like to thank the staff of the Marine Ecosystem Research Laboratory (MERL) for their guidance, insight, ideas, and overall support through this process. I have learned so much from my time working with the MERL staff, and their efforts were vital to the success of my research. Finally, I could not have done this without the support from my family and significant other. Their time spent proof reading, feedback, moral support, and technical support were vital to my success.

PREFACE

This thesis is original, unpublished, independent work by the author, V. Deingeniis. Data depicted in chapter 3 was collected by a variety of different organizations, this includes the Marine Ecosystem Research Laboratory (MERL) from the University of Rhode Island Graduate School of Oceanography (URI GSO). The MERL lab conducted the long-term deployment, maintenance, retrieval, and processing of water quality data. Water quality data went through extensive quality control and assurance steps by MERL staff before it was utilized in this study. Data collected and processed by the National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Information was utilized in this study for precipitation measures at the nearby T.F. Green international airport. Finally, data collected by the Rhode Island Department of Environmental Management (RIDEM) Office of Water Recourses, Shellfish Water Quality Program was utilized for fecal coliform measurements. Sampling efforts, data processing, and quality assurance, and control were conducted on these datasets by their respective working groups. Permission was granted by these respective groups before data was used in this study.

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CHAPTER 1

INTRODUCTION

Statement of the Problem

The water quality of Greenwich Bay is unfit for shellfishing, swimming, and for the health of marine organisms. Stormwater runoff from municipalities bordering Greenwich Bay has been proposed as a threat to the health of recreational, and commercial stakeholders, as well as marine organisms. Limits to stakeholders use of the watershed include shellfishing and beach closure events. In which both recreational, and commercial activates are prohibited over a certain period based on worsening water quality parameters. Hinderances to marine life include stress to organisms in their larval stage, the departure of mobile organisms, and in severe cases causing death. Nonpoint sources of pollution such as stormwater runoff and groundwater influx pose the greatest threat to the water quality of Greenwich Bay. Nonpoint sources of pollution are difficult to monitor, and trace back to their point of introduction. Point sources of pollution such as effluent from Wastewater Treatment Facilities (WWTF) is another threat to the water quality of Greenwich Bay. While point sources of pollution are not as difficult to monitor as nonpoint sources of pollution, they present a significant contribution of pollutants into the watershed. Nitrogen is a common form of a nutrient that is present in both nonpoint and point sources of pollution. Excess nitrogen, also known as eutrophication, is a fuel source for phytoplankton growth which are commonly known as algal blooms. Algal blooms require a high demand for available oxygen, often leading to a sharp decrease in the amount of available oxygen in the watershed. Hypoxia, or anoxia in extreme cases is the phenomenon where there is a severe lack of available dissolved oxygen in a marine system. Hypoxic and anoxic conditions cause adverse effects to marine organisms such as in fish kill events, as well as causing hinderances to stakeholder groups through beach closures. Sources of nitrogen are poorly understood in the watershed, and there needs to be further investigation into mitigating the quantity of nitrogen that enters the watershed. Bacteria, especially fecal coliform is another pollutant that degrades the water quality of Greenwich Bay and presents health risks to humans who encounter polluted waters. Fecal coliform is used as an indicator for both beach and shellfishing closures, expressing how concentrations of fecal coliform hinder stakeholder groups from utilizing the watershed. Sources of fecal coliform, especially as a nonpoint source of pollution is poorly investigated and requires further research. Current state and federally mandated regulations are in place to safeguard stakeholders from harm associated with impaired waters, as well as protect marine organisms from water quality conditions that cause stress or harm. Beach and shellfishing closures, as well as hypoxic and anoxic conditions are clear examples of Greenwich Bay waters not meeting current management efforts.

Justification for and Significance of the Study

A variety of ambient water quality parameters for Greenwich Bay do not meet water quality standards for safe recreation and shellfishing activities; this is evident through beach closures as well as long term and conditional shellfishing closures. Waters of the US can be classified as impaired based on their designated uses, “over a third of estuarine waters (36% or 57.4 square miles) are impaired for one or more designated use” (Rhode Island Department of Administration Division of Planning, 2016). This includes specific locations within Greenwich Bay and is a driving factor for this study. Long term ambient water quality monitoring is used to assess areas with highest pollutant concentrations, as well as determining how said pollutants are entering the marine ecosystem. Finally, water quality monitoring is used to determine how management decisions can be made to protect the environment. Regulations surrounding stormwater and wastewater management rely heavily on ambient water quality monitoring; it is an invaluable tool in determining where improvements need to be made. Studying the water quality of Greenwich Bay and the surrounding regulatory framework associated with stormwater management makes it possible to state more targeted policy alternatives to combat the negative impacts of untreated stormwater runoff.

Water Quality Goals of Greenwich Bay:

Specific bodies of water within the US have different standards and thresholds for different pollutants based on the desired use for said body of water. These are known as water quality standards and there are many individual areas of Greenwich Bay which are designated by their different water quality standards (Nathanson, 2023). In general water quality standards are intended to protect public health, safety, and welfare, enhance the quality of water, and serve the purpose of existing regulation like the Clean Water Act. As listed in the Clean Water Act (CWA), the federal objective for surface waters of the US is to ensure that waters can be “fishable, and swimmable.” People should be able to safely recreate in and around Greenwich Bay especially through primary and secondary recreational contact. “Primary recreational contact” under the Rhode Island General Law is defined as any recreational activities in which there is prolonged and intimate contact by the human body with the water, involving considerable risk of ingesting water. These activates include swimming, diving, water skiing and surfing. (R.I. Gen. Laws, 2023) “Secondary recreational contact” is defined as any recreational activity in which there is minimal contact by the human body with the water, in this case the probability of ingestion of the water is minimal. These activities include boating and fishing (R.I. Gen. Laws, 2023), it is important to note that fishing in this case does not include the consumption of finfish or shellfish. The waters of Greenwich Bay should allow for the propagation and growth of fish species without negative impact from discharged pollutants. In the past and the present many areas of Greenwich Bay do not meet these federally mandated standards; additionally, many areas of Greenwich Bay do not meet the state mandated standards assigned to them. Some areas are hotspots which often rarely comply with state level standards while others do not meet standards on a conditional basis. This is evident through beach closures, and shellfishing closures. Beach closures occur at many of the recreational areas within the Greenwich Bay watershed and aim to limit humans and pets primary contact with the waters of Greenwich Bay. Beach closures are a result of pollutants entering bay waters that can cause harm to humans and pets, especially if water is accidently consumed when swimming. Shellfishing closures occur in Greenwich Bay in the form of conditional shellfishing closures and long term prohibited closures, in both cases commercial and recreational harvest of shellfish species is not allowed to safeguard humans from sicknesses and diseases that are common when consuming shellfish from polluted waters. Long term shellfishing closures are often year-round closures that are a result of polluted waters that do not reach the threshold for safe consumption of shellfish at any point during the year. Conditional closures occur because the water quality of the area does not meet the threshold for safe shellfish consumption for a period; this can be a few days up to a few months depending on the water quality parameters. Conditional closures of shellfishing within Greenwich Bay occur with a 0.5 inch to 7-day rain closure to protect public health from elevated fecal coliform levels due to stormwater runoff (RIDEM office of water resources, 2020). This entails that when a half inch of rain occurs within the Greenwich Bay watershed, shellfishing is prohibited for seven days. The conditional closure area of Greenwich Bay can be seen in figure 2 as GA8-5 shellfishing in all other sections of Greenwich Bay are permanently prohibited. In 2017 a seasonal closure for the month of December was applied to Greenwich Bay in the GA8-5 area, in which during the month of December shellfishing in the area was prohibited due to concentrations of fecal coliform. This seasonal closure ceased after May of 2017 due to improvements in concentrations of fecal coliform in the area; currently there are no seasonal closures within the waters of Greenwich Bay. The Rhode Island General law states that conditional closures are, “the water areas in Rhode Island overlying shellfish grounds herein described are from time to time found to be in an unsatisfactory sanitary condition for the taking of shellfish for human consumption and are declared to be polluted areas at those times” (RI General Laws, 1956). Once water quality parameters meet the threshold for safe shellfish consumption the conditionally closed areas are often re-opened with shellfishing as normal. There are historical as well as present day examples of beach closures, conditional, and long-term closures to shellfishing across many areas of Greenwich Bay;

this highlights the need for further investigation into the driving factors for these unsafe conditions and what can be done in terms of land use to meet the water quality standards set forth by both federal and state governments.

Water Body Common name	Cause of impairment	Classification and Partial Use	DO classifications	Fecal coliform Classification for Swimming (primary contact)	Fecal Coliform classification for Shellfishing
Apponaug Cove	Nutrients, Hypoxia	SB	4.8 mg/l shall be considered protective of Aquatic Life Uses.	Primary Contact Recreational/Swimming Criteria - Not to exceed a geometric mean value of 50 MPN/100 ml and not more than 10% of the total samples taken shall exceed 400 MPN/100 ml, applied only when adequate enterococci data are not available.	Shellfishing is not permitted in these waters
Brush Neck Cove	Pathogens, Nutrients, Hypoxia	SA			Shellfishing Criteria: - Not to exceed a geometric mean MPN or MF (mTEC) value of 14 per 100ml and not more than either 10% of the estimated 90th percentile of the samples shall exceed an MPN value of 49 per 100ml for a three-tube decimal dilution or 31 cfu per 100ml for MF (mTEC).

Buttonwoods Cove	Pathogens, Nutrients, Hypoxia	SA			Shellfishing Criteria: - Not to exceed a geometric mean MPN or MF (mTEC) value of 14 per 100ml and not more than either 10% of the estimated 90th percentile of the samples shall exceed an MPN value of 49 per 100ml for a three-tube decimal dilution or 31 cfu per 100ml for MF (mTEC).
Warwick Cove	Nutrients, Hypoxia	SB + SA			Shellfishing Criteria: - Not to exceed a geometric mean MPN or MF (mTEC) value of 14 per 100ml and not more than either 10% of the estimated 90th percentile of the samples shall exceed an MPN value of 49 per 100ml for a three-tube decimal dilution or 31 cfu per 100ml for MF (mTEC).
North		SB			Shellfishing is not permitted in these waters

South		SA			Shellfishing Criteria: - Not to exceed a geometric mean MPN or MF (mTEC) value of 14 per 100ml and not more than either 10% of the estimated 90th percentile of the samples shall exceed an MPN value of 49 per 100ml for a three-tube decimal dilution or 31 cfu per 100ml for MF (mTEC).
In the vicinity of Captain's Shellfish area		SB			Shellfishing is not permitted in these waters
Greenwich Cove	Nutrients, Hypoxia	SB + SB1			Shellfishing is not permitted in these waters
North		SB			Shellfishing is not permitted in these waters
South		SB1			Shellfishing is not permitted in these waters

Greenwich Bay Proper	Pathogens, Nutrients, Hypoxia	SA			Shellfishing Criteria: - Not to exceed a geometric mean MPN or MF (mTEC) value of 14 per 100ml and not more than either 10% of the estimated 90th percentile of the samples shall exceed an MPN value of 49 per 100ml for a three-tube decimal dilution or 31 cfu per 100ml for MF (mTEC).

Table 1: Water quality classifications

Subwaters of Greenwich Bay and their appropriate classification which dictates their usage as well as acceptable pollutant threshold. As well as possible cause of impairment if applicable. Data source: Water Quality Regulations (250-RICR-150-05-1) as well as, State of Rhode Island 2022 Impaired Waters Report.

CHAPTER 2

REVIEW OF LITERATURE

Description of Greenwich Bay

Greenwich Bay is a shallow embayment within the greater Narragansett Bay, which is an estuary system where fresh and saltwater mix. Greenwich Bay is approximately 5 square miles in size, is one of the largest embayments within Narragansett Bay, and connects to the upper West Passage of Narragansett Bay. Greenwich Bay has five protected coves which are a major source of freshwater influx into the rest of Greenwich Bay. These coves come with longer flushing times where there is less circulation and longer times between total transport of water in and out of the greater Greenwich Bay. Greenwich Bay and its watershed encompass two major suburban areas; East Greenwich and the city of Warwick include many homes and businesses that are in direct contact with the waters and tributaries of Greenwich Bay. The Greenwich Bay watershed is surrounded by 22.8 miles of shoreline which comprises suburban lands either in the town of East Greenwich or the city of Warwick. These two suburban locations make up a large population of people and industries that have a direct impact on the overall water quality of Greenwich Bay. Greenwich Bay is used for a variety of different commercial, recreational, and leisure activities including, the harvest of shellfish, as well as both commercial and recreational fishing, commercial and recreational boating, as well as being a destination for beachgoers, and a valuable viewshed for tourists.

The five protected coves within Greenwich Bay are Apponaug Cove, Buttonwoods Cove, Brushneck Cove, Warwick Cove, and Greenwich Cove. Small tributaries flow into these embayments which eventually flow into Greenwich Bay proper. These tributaries include Hardig Brook which flows into Apponaug Cove, Tuscatucket Brook which flows into Brushneck and Buttonwoods Cove, the Maskerchugg River which flows into Greenwich Cove, as well as other smaller tributaries which are unnamed. These tributaries make up a large majority of the freshwater inputs into Greenwich Bay. The two largest freshwater inputs into Greenwich Bay are Hardig Brook and the Maskerchugg River. These two sources represent more than 60 percent of the freshwater inputs into Greenwich Bay. The remaining 40 percent of freshwater inputs are derived from smaller tributaries, the East Greenwich WWTF, direct surface runoff, groundwater flow and stormwater outfalls into the Bay (Pesch et al. 2012). An additional source of freshwater into Greenwich Bay is the Hunt River which is a small freshwater river that flows into the greater Potowomut River and eventually into Narragansett Bay. The Hunt and Potowomut rivers do not directly flow into Greenwich Bay proper like some of the other rivers of Warwick and East Greenwich. The Hunt River is one of the only rivers in the area that has long term and continuous flow data monitoring.

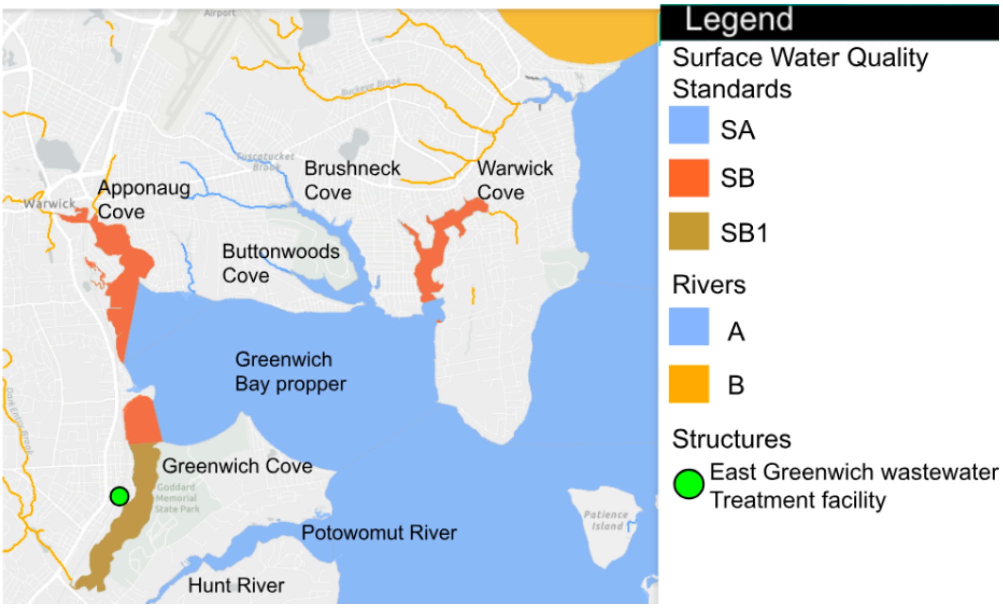


Figure 1: Greenwich Bay surface water quality standards map

Surface water quality standards are based on designated uses such as swimming and shellfishing for human consumption. Most coves in Greenwich Bay are mapped as having fecal coliform levels that make them unsuitable for shellfishing for human consumption. Source: RIDEM Environmental Resource Map

The land use and population dynamics of these suburban areas has changed drastically over the past 85 years with the population in Warwick increasing almost 3-fold, the population of East Greenwich increasing about 2.5-fold, and the population of West Warwick increasing about 1.3-fold. From 1950 to 2000, the estimated population in the watershed doubled, from an estimated 25,500 to 49,400 individuals. Land use changes are a direct result of an increasing population, "Human population growth increases the demand for larger or new infrastructure, which leads to land conversion (primarily from forest land to urban land), with construction of new roads, buildings, and other utilities and amenities" (Narragansett Bay Estuary Program, 2017). From 1988 to 1995 developed land increased from 59.5% to 62%, while undeveloped land decreased from 40.5% to 37.9% (Pesch et al. 2012). In 1995, land use data showed that only 3% of land within the Greenwich Bay watershed was categorized as agricultural land, 17.9% as forest and 9% as wetlands, meanwhile 62% of land was classified as developed. Developed land was categorized as being residential, or commercial and industrial; out of the 62% of developed land, 46% of it was residential and 16% was considered commercial and industrial land (Pesch et al. 2012). Suburban lands, like ones found in East Greenwich and Warwick often have smaller densities of citizens rather than urban settings but end up having a higher percentage of developed land rather than urban areas which have higher densities of people in a smaller overall location. Each person in a suburban landscape effectively occupies more developed land than citizens in urban areas (Tu et al. 2006). These land use trends continued into the early 2000. In 2004 29% of the Greenwich Bay watershed consisted of impervious surfaces. Impervious surfaces consist of buildings, pavement, and other unnatural, solid surfaces that cause water and pollutants to flow aboveground rather than being absorbed and retained by soils or vegetation (Narragansett Bay Estuary Program, 2017). Some land use models utilize threshold ranges of impervious surfaces to determine different degrees of stream quality as reflected in aquatic life; Greenwich Bay as of 2017 consisted of 29.7% impervious surfaces. The threshold impervious surface coverage for not-supporting stream quality to support aquatic life is 26-60 percent, which puts the Greenwich Bay watershed in this category (Narragansett Bay Estuary Program, 2017). Impervious surfaces also generally do not decrease overtime, oftentimes only ever increasing as further development occurs. Greenwich Bay's 22.8-mile coastline follows these land use trends. In 2003 57% of the land within a 500-foot buffer of the Greenwich Bay shoreline was developed. This development consists of

47% residential land and 10% commercial and industrial land (Pesch et al. 2012). A result of these land use changes is directly related to the loss of coastal wetlands within Greenwich Bay, between 1868 and 2003 there was a 40% loss of coastal wetlands with most of this loss occurring in Apponaug, Brush Neck, Buttonwoods and Warwick Coves (the northernmost reaches of Greenwich Bay) (Pesch et al. 2012). Population dynamics and land use changes within the Greenwich Bay watershed are clearly a significant form of anthropogenic change that has a variety of negative impacts on the water quality of the Greenwich Bay watershed.

Nutrients as a driving factor for eutrophication, algal blooms, and hypoxia:

Nutrients like nitrogen and phosphorus are both necessary for the growth of plants and animals as well as support a healthy aquatic ecosystem. However, excess nutrients can contribute to algal blooms, low dissolved oxygen, fish disease, and brown tides (RIDEM, 2005). Excessive nutrients such as nitrogen in estuarine ecosystems affect primary production of phytoplankton, dissolved oxygen levels, water clarity, and the overall water quality (Narragansett Bay Estuary Program, 2017). When estuarine waters are hypoxic, they are limited in the amount of oxygen that is available for aquatic life to use to sustain themselves. Eutrophication or the abundance of nutrients in an estuary ecosystem is an ecological driver for the presence of hypoxic water conditions. As nutrients increase in an estuary there is a stark increase in primary production (eutrophication). This follows with a reduction in dissolved oxygen due to a fast increase in productivity and growth of macroalgae which uses most of the oxygen available. When these macroalgae die off their decomposition also uses a large percentage of the available oxygen, especially in near bottom waters, this contributes to hypoxic conditions in near bottom estuarine waters (Narragansett Bay Estuary Program, 2017). As estuarine waters lose dissolved oxygen it puts stress on aquatic organisms and in some cases causes marine life to relocate or in severe cases die off as in the 2003 Greenwich Bay fish kill. Therefore, monitoring the trends in nutrient loading into Greenwich Bay is an extremely important indicator of ecosystem conditions as well as give insight into the possible cascading negative impacts on estuarine ecosystems (Narragansett Bay Estuary Program, 2017). Continuous long term nutrient monitoring efforts are mandatory to understand which anthropogenic changes cause the highest flux of nutrients as well as how to properly mitigate the entrance of nutrients into the watershed.

Water quality standards:

Water quality standards are categorized within the State of Rhode Island General Laws, and are labeled as SA, SA{b}, SB, SB1, SB{a}, SB1{a}, and SC. (R.I. Gen. Laws, 2023) These water quality standards are depicted in figure 1 and give insight into what activities are supported and which are not supported based on water quality parameters as well as pollutant concentrations. Most of Greenwich Bays surface waters are classified as SA, these waters are approved for fish, and shellfish consumption, primary contact recreation, and secondary contact recreation. These uses can be practiced if pollutant concentrations for fecal coliform are within the designated thresholds enacted by the state for these use cases. In SA classified waters the state mandated fecal coliform threshold for safe primary recreation is 50 MPN per 100 ml. If this threshold is exceeded within SA classified waters, then swimming is prohibited until fecal coliform concentrations are reduced below the threshold. Shellfishing and fish consumption are allowed in SA classified waters if the concentration for fecal coliform is less than 14 MPN per 100ml. When fecal coliform concentrations exceed this threshold shellfishing and fish consumption are prohibited until these bacteria concentrations drop below this threshold.

The second surface water classification that is commonly found in Greenwich Bay are SB classified waters. This classification is less strict which means these areas often experience higher concentrations of pollutants and lower overall water quality. Examples of areas in Greenwich Bay that exhibit surface waters under the SB classification include the northern extent of Greenwich Cove, Apponaug Cove, and lastly northern Warwick Cove. Class SB waters are designated for primary and secondary contact recreation, fish and wildlife habitat, and shellfish harvesting for controlled relay and depuration, and shall have good aesthetic value (Rhode Island Department of Environmental Management, 2005). Shellfish consumption is not supported in SB classified waters unless proper relocation and depuration is practices, because of high concentrations of fecal coliform (303D list, 2015). These water quality standards give insight into some of the most prevalent pollutants that negatively affect both the local ecology as well as the stakeholders who recreate and fish in these areas. The current ambient water quality conditions of many areas within Greenwich Bay do not meet federal goals of “fishable, and swimmable” waters. There are areas that do meet these federal standards, but further management actions need to be taken to ensure more of Greenwich Bay meets these federal standards.

The Rhode Island state water quality standards are consistent with the CWA:

The Office of Water Resources (OWR) implements the state's Water Quality Standards Program; the Water Quality Standards Program is responsible for ensuring compliance with the Federal Clean Water Act (CWA). The purpose of this program is to restore, preserve, and enhance the water quality of Rhode Island waters. As well as to maintain existing uses and to protect the waters from pollutants so that the waters shall, where attainable, be fishable and swimmable, and be available for all designated uses and thus assure protection for the public health welfare, and the environment. These objectives are implemented through the water quality standards which are a fundamental element of the state's Water Quality Regulations (RIDEM, 2023). Under the Rhode Island General Laws, water quality regulations are put in place to restore, preserve, and enhance the physical, chemical, and biological integrity of the waters of the state. These regulations are designed to maintain existing water uses and to serve the purposes of the Clean Water Act (R.I. Gen. Laws, 2023). By adopting federal regulations as described by the CWA, the state of Rhode Island accepts federally mandated thresholds for specific water quality standards. These standards and thresholds are the determining factor when analyzing ambient water quality and pollutant data.

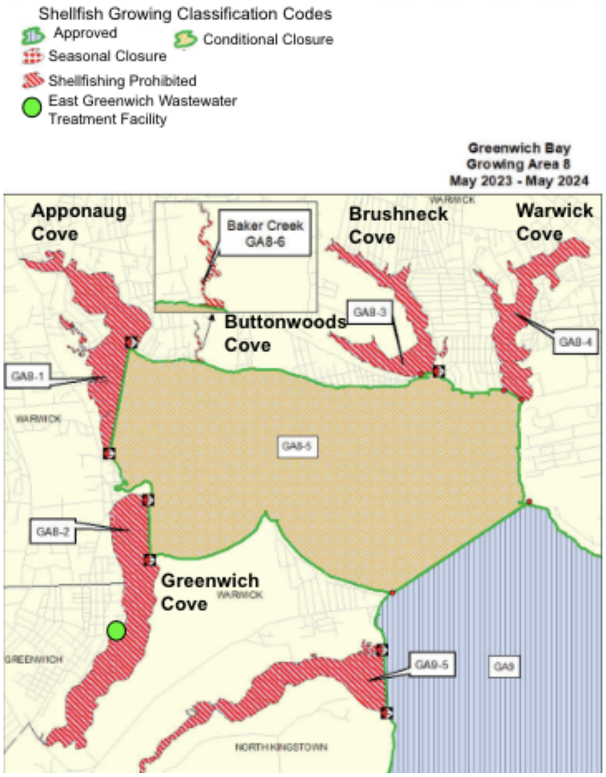


Figure 2: Shellfishing closure map of Greenwich Bay

Map of Greenwich Bay where shellfishing is prohibited (red) as well as where shellfishing is conditionally prohibited (tan) depending on state mandated pollutant thresholds. These closure areas were updated in 2023 and will be used through May of 2024. Source: Rhode Island Department of Environmental Management (RIDEM).

CHAPTER 3

METHODOLOGY

Data:

One of the main sources of ambient water quality data that was used in this study was the use of the Narragansett Bay Fixed-Site Monitoring Network (NBFSMN) this network of land based, and buoy-based sampling locations provide ambient water quality data from the early 2000s to the present day. These monitoring efforts are conducted by several organizations including the Rhode Island Department of Environmental Management (RI DEM) as well as the University of Rhode Island Graduate School of Oceanography (URI GSO). The data compiled from these sampling locations is processed by the URI-GSO Marine Ecosystem Research Laboratory as well as made available via URI and DEM websites (RI DEM, 2017). Data from two different sampling locations were used in this study, the first sampling location is the Greenwich Bay fixed monitoring land-based site, and the second is from the Sally Rock sampling location which is a buoy-based site. Both the Greenwich Bay and Sally Rock sampling locations have a “surface” sonde, located about a meter below the surface. As well as a “bottom” sonde, located about 0.5 m above the bottom. These sondes collect data every 15 minutes for a range of parameters including temperature, salinity, DO%, DO mg/L, depth, pH, and surface Chl-a (RI DEM, 2017).

Fecal coliforms are the main bacteria used to determine which areas of estuarine waters are fit or unfit for swimming and shellfishing. Fecal coliform measures are carried out by the Rhode Island Department of Environmental Management (RIDEM) Office of Water Resources (OWR) Shellfish Water Quality Program. Surface water samples were collected throughout Greenwich Bay at 20 different locations, these locations include all five embayments as well as locations within Greenwich Bay proper. Water samples are analyzed by the Rhode Island Department of Health (RIDOH) Water Microbiology Laboratory, to determine the presence of fecal coliform bacteria in samples. The procedure used within the analysis of water samples is the standard fecal coliform membrane filtration method (sm48 mTEC) (RIDEM, Office of Water Resources, 2022). Fecal coliforms are measured in the form of cfu/100 ml and taken on a monthly or twice monthly basis, from 2005 to 2023.

Precipitation is a vector of pollutants as well as a driver for a variety of different hydrological factors which is why it was utilized for this study. Precipitation values were collected by the National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Information. This sampling station is located at the Rhode Island T.F. Green International airport in Warwick Rhode Island. This sampling location is in very close proximity to Greenwich Bay and provides an accurate measure for precipitation, and ambient air temperature. Precipitation is recorded daily and includes rain, and melted snow in inches, measurements are taken as 24 hour amounts which end at the observation time. Air temperature is also recorded daily as a maximum and minimum in Fahrenheit, these measures are also taken as 24 hour amounts which end at the observation time. Precipitation values are summarized by month, this entails that for each month between 2005 and 2023 the total sum of precipitation was obtained. Air temperature was presented as an average maximum and minimum by month. Both monthly total precipitation and monthly average maximum temperature were utilized within this study, especially in statistical tests.

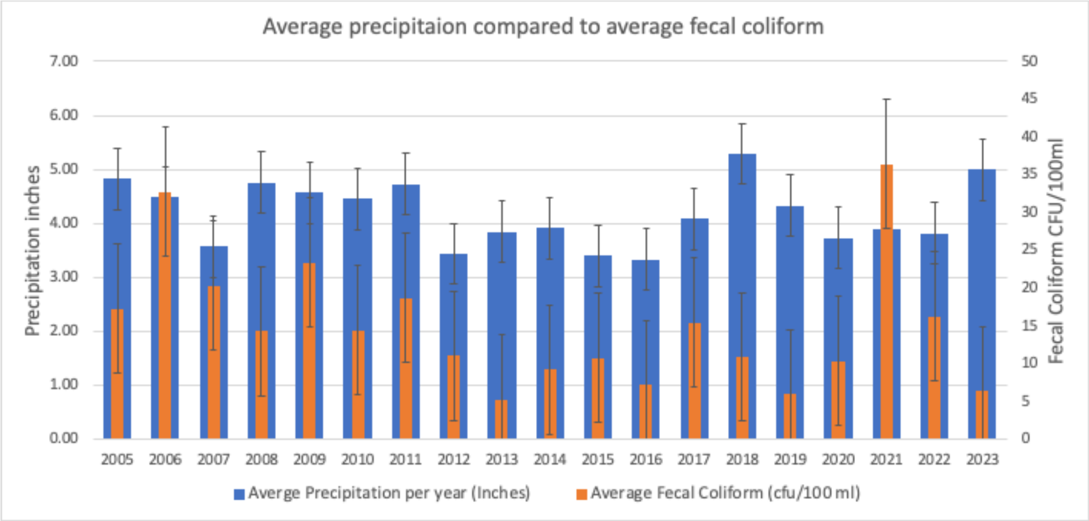


Figure 3: Average precipitation compared to yearly average fecal coliform Average precipitation compared to average fecal coliform across all of Greenwich Bay Samples were taken at 20 different locations in Greenwich Bay and were collected from 2005 to 2023. Precipitation is plotted per year obtained from monthly averages and measured at the T.F. Green international airport. Years that experience higher average precipitation are not associated with elevated concentrations of fecal coliform. Sources: RI DEM, Office of Water Resources, Shellfish Water Quality Program for fecal coliform measurements and NOAA National Centers for Environmental Information for precipitation measurements.

Another vector of pollutants and an environmental driver for hydrological factors within Greenwich Bay is river flow data from freshwater rivers flowing into Greenwich Bay. Hunt river flow was utilized in this study; data was obtained daily from January 2005 to December 2023. The Hunt River is a small freshwater river that flows into the greater Potowomut River and eventually into Narragansett Bay just south of the mouth of Greenwich Bay. The Hunt and Potowomut rivers do not directly flow into Greenwich Bay proper like some of the other rivers of Warwick and East Greenwich. The Hunt River is one of the only rivers in the area that has long term and continuous flow data monitoring. River flow was collected as a discharge rate in cubic feet per second. The monitoring station is in the Hunt River which is in East Greenwich Rhode Island. These monitoring efforts are completed by the U.S. Geological Survey (USGS). Daily discharge rates were utilized to obtain both monthly and yearly average discharge rates for the Hunt River. These values were utilized in this study, especially in statistical tests.

The final piece of data that was utilized in this study was the RI DOCS number of hypoxic days dataset. This dataset makes use of the RIDEM-adopted software application called Dissolved Oxygen Criteria Software for Rhode Island (DOCS-RI; SAIC 2006) to calculate season-cumulative (June 1st to September 30th) days exceedance over state mandated thresholds for hypoxic conditions within Narragansett Bay. From a regulatory standpoint hypoxia refers to the conditions where the concentration of dissolved oxygen decreases to the point where organisms are adversely affected (Stoffel, Kiernan, 2009). The State of Rhode Island has adopted dissolved oxygen criteria that reflect the following thresholds for estuarine surface waters: 4.8 mg/l instantaneous values, 2.9-mg/l per 24- hour average value, and 1.4 mg/l per one hour average (Stoffel, Kiernan, 2009). These criteria are based on the lethality of low oxygen to various marine organisms at various life stages in Narragansett Bay. These values were adapted from the federal Environmental Protection Agency (EPA) guidance, the Rhode Island dissolved oxygen criteria for saltwater are designed to provide protection to all life stages from larval through adult (Stoffel, Kiernan, 2009). The RI DOCS data set utilizes near bottom dissolved oxygen concentration data from the Fixed-Site Monitoring Network (NBFSMN) to determine the number of hypoxic days at two Greenwich Bay sampling locations. The RIDOCS number of hypoxic days is based on three different dissolved oxygen values for determining hypoxic conditions within the Greenwich Bay watershed. These three values are 4.8, 2.9 and 1.4 mg/l. Three different values are used to measure to determine the number of hypoxic days to measure the intensity of hypoxic conditions. These three dissolved oxygen concentrations are derived from Rhode Island General Law. Salt waters with a dissolved oxygen concentration above an instantaneous value of 4.8 mg/l shall be protective of aquatic life. However, when concentrations of dissolved oxygen dip below the 4.8 mg/l the waters shall not be less than 2.9 mg/l for more than 24 consecutive hours, or less than 1.4 mg/l for more than 1 hour (R.I. Gen. Laws, 2023) The RIDOCS takes these values established in legislation into account and utilizes them as the three thresholds to establish the number of hypoxic days. The RI DOCS calculation makes use of data from NBFSMN bottom sondes at both the Greenwich Bay and Sally Rock sampling locations which can be seen in figure 6. This data can provide both duration and intensity of hypoxia within Greenwich Bay which is crucial in understanding the seasonal trends and variation in hypoxic conditions in the bay. The RI DOCS dataset is integral to the approach taken by state regulators to assess whether seasonal ambient water quality conditions in Narragansett Bay follow the saltwater dissolved oxygen criteria (Codiga et al, 2009). This dataset provides outputs at both the Greenwich Bay and Sally Rock sampling locations as seen in figure 6. These stations are the same locations in which near surface and near bottom ambient water quality measures are recorded within the Narragansett Bay Fixed-Site Monitoring Network (NBFSMN) This dataset provides the number of hypoxic days at the Greenwich Bay sampling location from 2003 to 2022, and from 2008 to 2022 at the Sally Rock Sampling location. Outputs are divided into monthly values and include data from May to October, as hypoxic conditions rarely occur outside of this monthly time frame.

CHAPTER 4

FINDINGS

Geographic areas of most concern:

The results depicted through the figures and tables listed above give insight into the geographic locations of Greenwich Bay that experience the highest concentrations of specific pollutants at specific points of time during the year. These results also provide which pollutants are more prevalent than others, and finally, how environmental processes lead to an increase in said pollutants. The physical characteristics of Greenwich Bay give insight into why certain areas have higher concentrations of pollutants as well as lower overall water quality. Small, shallow, protected embayment's with large amounts of freshwater influx from rivers or from stormwater runoff are often areas where pollutants become trapped and do not get mixed into deeper, and more circulated waters. This phenomenon is known as the flushing time of a specific location, and it plays a large role in understanding why certain areas experience higher concentrations of pollutants for longer periods of time. Greenwich Cove, Apponaug Cove, and Warwick Cove are all examples of embayment's within Greenwich Bay that exhibit these water quality issues. These embayment's have SB and lower surface water quality standards they have less strict thresholds for the number of pollutants that can be present during a given time, and the designated uses allowed in those waters are not as extensive as in waters with higher water quality standards, this is highlighted in both figure and table 1.

Areas of highest concern based on concentrations of fecal coliform in Greenwich Bay:

Shellfishing is closed in all 3 of the previously mentioned embayments. This is highlighted in figure 2 with the long-term closure of shellfishing in these areas. The embayment's found in Greenwich Bay are areas of highest concern when it comes to water quality issues, these embayment's which include Apponaug Cove, Brush Neck Cove, Buttonwoods Cove, Warwick Cove, and finally Greenwich Cove. Future management efforts should be directed to these areas, as they are the areas of highest concern. The average fecal coliform by sampling site in figure 4 shows that on average sites 10, 26, and 22 had the highest concentrations of fecal coliform between the years of 2005 and 2023. These sites are in Apponaug Cove, Brushneck Cove, and Warwick Cove respectively. All three of these sampling locations experienced average concentrations of fecal coliform that exceeded the state mandated threshold for safe shellfishing practices; this threshold is set at 14 cfu per 100ml. Additionally the concentration of fecal coliform at site 10 was over the state mandated threshold for safe primary contact recreation which is set at 50 cfu per 100 ml. Apponaug cove contains the highest concentration of fecal coliform out of any other location within Greenwich Bay. While figure 4 represents the areas of highest concern it does not provide insight into the temporal trends of fecal coliform. Figure 10 depicts concentrations of fecal coliform over the time at sites 10, 26, and 22 which are described above. Figure 10 depicts points in time in which concentrations of fecal coliform at these three sites exceed state mandated threshold for shellfishing and swimming, those being 14 cfu/100 ml and 50 cfu/100ml. All three coves experience points that exceed both thresholds with

Apponaug cove experiencing the highest number of exceedances over time which aligns with the results depicted in figure 4. These three coves also experience a high number of exceedances in the early 2000s with most of the largest values occurring prior to 2012. Figure 10 also shows that Warwick and Brushneck Coves are experiencing a smaller number of fecal coliform exceedances with the most recent large-scale exceedances occurring in 2021. On the other hand, Apponaug Cove still experiences large concentrations of fecal coliform as recent as 2023. These observations prove that Apponaug Cove is the area of highest concern when it comes to concentrations of fecal coliform. Furthermore, appendix figure 5 depicts concentrations of fecal coliform at two different sampling locations regarding three beaches that are separately monitored for presence of fecal coliform. The fecal coliform measures around beach closure events do not prove to show a significant relationship with precipitation events as depicted in appendix figure 5. Dedicated fecal coliform monitoring conducted by the Rhode Island Department of Health (RI DOH) at these three beaches is a more accurate method of monitoring bacteria conditions at beaches, while Rhode Island Department of Environmental Management (RIDEM) sampling efforts are better suited for determining shellfishing closures.

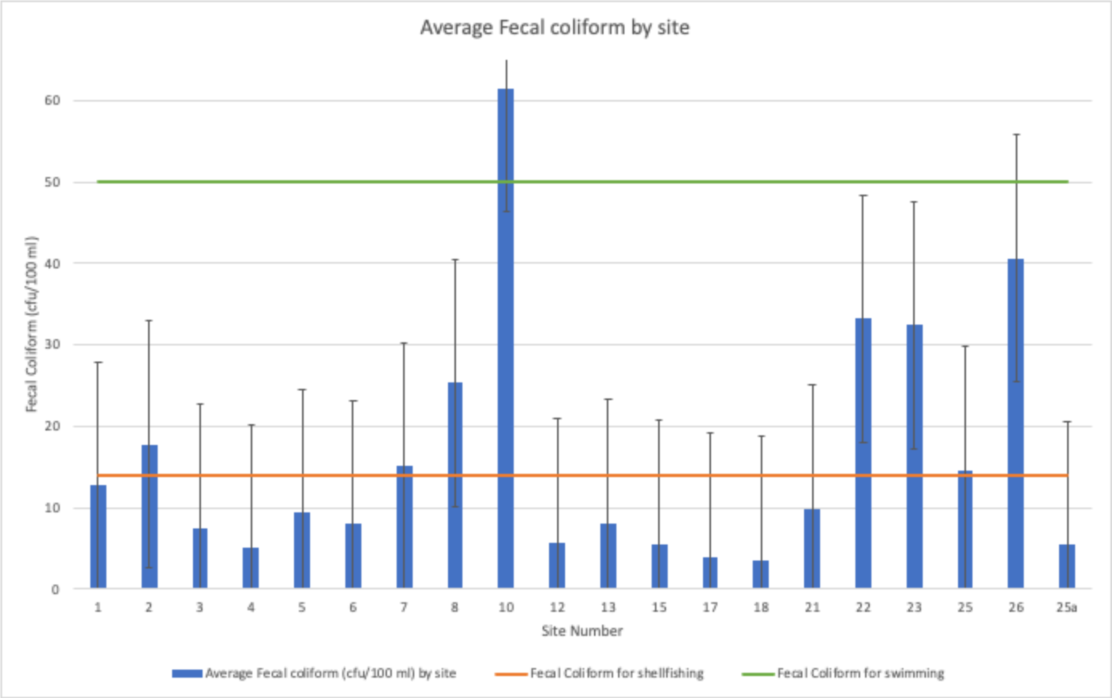


Figure 4: Concentrations of fecal coliform by sampling location

Fecal coliform is collected at 20 different sampling locations (see Figure 6) from 2005-2023 and average values are plotted over time. The three locations with the highest average fecal coliform are sites 10 (Northern Apponaug Cove), 26 (Northern Brushneck Cove), and 22 (Warwick Cove). Error bars were fitted using the standard deviation of the dataset. Data source: RI DEM, Office of Water Resources, Shellfish Water Quality Program.

Concentrations of fecal coliform in Greenwich Bay disproportionately affect specific areas over others. Tables 2 and 3 highlight the number of samples, and average fecal coliform concentrations that are over the threshold for safe primary contact and shellfishing. This narrows data from figure 4 into looking at the samples that exclusively exceed the threshold for the desired uses of shellfishing and swimming and covers the same time frame of 2005 to 2023. The goal of these tables is to exclude samples that are within the state mandated threshold for safe swimming and shellfishing and solely focusing on the areas of highest concern. The sampling stations in

Greenwich Bay that experience the highest number of samples that exceed the state mandated threshold for primary contact through recreation like swimming are sites 10, 26, and 23. Site 10 has the highest number of samples over the threshold, while 26 was the second highest and finally site 23 was the third highest. Again, site number 10 is Apponaug Cove, site 26 is Brush Neck Cove and finally site 23 is the northern extent of Warwick Cove. These embayments within Greenwich Bay are the areas where fecal coliform concentrations are highest. Due to inconsistencies in sampling efforts conducted by the RIDEM, some locations were sampled more than others. Regardless, sites 10 and 23 were sites with the largest and third largest number of samples that exceeded state mandated thresholds for swimming and had a one sample difference in the number of total samples. Site 26 had the second highest number of samples that exceeded the state mandated threshold for swimming and had a total of 170 samples. This site was sampled considerably less than other locations and still resulted in the second highest number of samples that exceed the threshold. Another important aspect of these findings is in the ratio of samples that exceed the state mandated threshold out of the total number of samples, there are 224 samples out of 4,003 total samples that exceeded the state mandated threshold for safe swimming taken across all of Greenwich Bay, from 2005 to 2023. This shows that only .055% of the total data was over the threshold for safe swimming in Greenwich Bay. This is an extremely low number, but it proves that there are locations and times where the waters of Greenwich Bay are not in compliance with state and federally mandated thresholds for primary contact. Finally, table 2 includes the average fecal coliform concentrations over the threshold for safe primary contact. These three locations are highlighted with the same method as described above with sites 22, 10, and 23 having the highest averages. These locations are Warwick Cove, Apponaug Cove, and finally Northern Warwick Cove. This does not perfectly align with the three sites with the highest number of samples over the state mandated threshold, but it does show that again the embayments in the northern portion of Greenwich Bay is a hotspot for the highest concentrations of fecal coliform out of all of Greenwich Bay.

Table 3 utilizes the same data in table 2 with the only change being the threshold used. Table 3 utilizes the state mandated threshold for safe shellfish consumption as a measure to determine which areas are safe for commercial or recreational shellfishing to occur. This threshold is 14 cfu/100 ml and the data in table 3 shows all samples that exceed that value. The three sampling locations that experienced the greatest number of samples that exceed the state mandated threshold for safe shellfishing are 10, 23, and 8. These sampling locations are Northern Apponaug Cove, Northern Warwick Cove and finally Southern Apponaug Cove respectively. These three sampling locations had a very similar number of overall samples taken, with site 8 having 205 total samples, site 23 having 203 samples and finally site 10 having 202 samples. This shows that oversampling or over representation was not conducted because all three of these sites had an extremely similar number of total samples. Like the conclusions gained from table 2, table 3 shows the Northern embayments of Greenwich Bay exhibiting the highest number of samples that exceed state mandated thresholds for shellfishing. Table 3 provides that there were 799 samples that were over the state mandated threshold for safe shellfishing, across all sampling locations from 2005 to 2023, again out of the total 4,4003 samples, 5.01% of total samples were in excess and unfit for shellfishing. This is a much higher result than in table 2 because the threshold required for safe shellfishing is much more stringent than the threshold for swimming. Shellfishing demands higher water quality conditions than those required for swimming. Finally, the three sites with the highest average concentration of fecal coliform over the threshold for safe shellfishing are sites 26, 10, and 23. These sampling sites are in Brush Neck Cove, Northern Apponaug Cove and finally Northern Warwick Cove. Again, this proves that the Northern embayments within Greenwich Bay are the locations where fecal coliform concentrations are the highest by average.

Station ID	**# Of total samples**	**# Of samples that exceed 50 cfu/100 ml**	**Average of Fecal coliform over primary contact threshold (50 cfu/100 ml)**
1	185	8	107.13
2	201	16	114.31
3	204	2	70.50
4 (Goddard State Park Beach)	205	1	96.00
5	205	7	112.29
6	206	6	99.17
7	206	8	166.55
8	205	20	166.55
10 (Apponaug Cove)	202	49	197.44
12	206	1	150.00
13	204	9	88.22
15	205	4	71.00
17	205	1	93.00
18	205	0	NA
21 (Oakland Beach)	205	9	83.11
22 (Warwick Cove)	203	16	306.88
23 (Northern, Warwick Cove)	203	25	192.84

25 (City Park Beach)	174	9	140.22
26 (Brush Neck Cove)	170	31	182.26
25A	205	2	105.50

Table 2: Bacteria criteria for swimming

This table excludes fecal coliform measures under 50 cfu/100ml, samples were taken from 2005 to 2023. This is the threshold for safe primary contact like swimming with surface waters within Rhode Island, as described in RI state law. Numbers highlighted in red, orange, and yellow follow a descending order with red being the largest and yellow being the third largest average concentrations as well as largest number of samples that exceed the state mandated threshold of 50 cfu/100ml. Data source: RI DEM, Office of Water Resources, Shellfish Water Quality Program.

Station ID	**# Of total samples**	**# Of samples that exceed 14 cfu/100 ml**	**Average of Fecal coliform over the threshold for shellfishing (14 cfu/100 ml)**
1	185	39	41.73
2	201	60	49.40
3	204	33	28.94
4	205	16	28.06
5	205	28	47.96
6	206	23	47.22
7	206	44	57.87
8 (Southern Apponaug Cove)	205	69	67.43
10 (Northern Apponaug Cove)	202	124	97.10
12	206	17	32.44
13	204	22	53.05
15	205	17	34.12
17	205	9	31.22
18	205	8	21.00
21	205	31	42.23

22	203	63	96.76
23 (Northern, Warwick Cove)	203	76	79.49
25	174	37	53.51
25A	170	14	39.21
26 (Brush Neck Cove)	205	65	99.38

Table 3: Bacteria criteria for shellfishing

This table excludes fecal coliform measures under 14 cfu/100ml, samples were taken from 2005 to 2023. This is the threshold for safe shellfishing within Rhode Island, as described in RI state law. Numbers highlighted in red, orange, and yellow follow a descending order with red being the largest and yellow being the third largest average concentrations as well as largest number of samples that exceed the state mandated threshold of 14 cfu/100ml. Data source: RI DEM, Office of Water Resources, Shellfish Water Quality Program.

Areas of highest concern based on hypoxia in Greenwich Bay:

Hypoxic events in Greenwich Bay do not occur year-round and often occur during the months of July and August as described in figure 7. Data in figure 7 is taken from two long term ambient water quality monitoring stations, these stations monitor for near surface and near bottom dissolved oxygen. Figure 7 shows hypoxic conditions at the Greenwich Bay sampling location which is marked with a blue diamond in figure 6. Figure 7 also depicts the same information for the Sally Rock sampling location, depicted as a red diamond in figure 6. For both the Greenwich Bay and Sally Rock sampling locations July and August are the two months in which hypoxic conditions were most observed. Based on the Greenwich Bay sampling location the total number of hypoxic days per year is slowly declining with 2017 being the last highest year and 2009 being the year with the largest number of hypoxic days. The number of yearly hypoxic days as depicted in figure 7 is further validated with the information provided by figure 9. Figure 9 depicts monthly average near bottom dissolved oxygen at the same sampling location found with the blue diamond in figure 6. The months with the lowest average dissolved oxygen concentrations are July and August as seen in both figure 7 and 9. Figure 9 also includes the state mandated threshold for dissolved oxygen concentrations that are protective for aquatic life. This value is set at 4.8 mg/l in which summer months especially July and August exhibit average dissolved oxygen concentrations below said threshold. This is consistent throughout the entire time frame of 2005 to 2022 with the near bottom dissolved oxygen concentration reaching similar levels year after year. This suggests that the months of July and August are when aquatic species are at their most threatened state because of the continuous low dissolved oxygen concentrations that are experienced during these two months. Based on the long-term monitoring of hypoxic conditions in Narragansett Bay conducted by the Rhode Island Department of Environmental Management (RIDEM) it has been determined that hypoxic conditions were naturally rare until humans significantly altered its patterns (RIDEM, 2022). Specific monitoring of Hypoxia in Greenwich Bay began in the year 2001 and has continued overtime. Management efforts should be directed towards improving the conditions of Greenwich Bay in such that conditions during the months of July and August reflect bottom dissolved oxygen concentrations that better support wildlife, as well as limit the number of hypoxic days which again cause harm to wildlife as well as local stakeholder groups.

The Sally Rock sampling location’s results suggests very similar conclusions as the Greenwich Bay sampling location includes years 2008-2022. Although hypoxic days are experienced at both the Greenwich Bay and Sally Rock sampling location, the Sally Rock location on average had a smaller number of hypoxic days per year. Sally Rock experienced the last highest number of hypoxic days in 202, and the highest recorded number of hypoxic days was in 2009. The monthly average near bottom dissolved oxygen concentration depicted in figure 9 further supports the conclusions suggested from figure 7. Like the Greenwich Bay sampling location, the Sally Rock site experiences the lowest concentration of near bottom dissolved oxygen during the months of July and August. Figure 9 also shows the same state mandated threshold for dissolved oxygen concentrations that are protective for aquatic life uses which is set at 4.8 mg/l. Interestingly, the Sally Rock sampling location depicted less consistent average near bottom dissolved oxygen concentrations during the months of July and August compared to the Greenwich Bay sampling location. Years like 2016 and 2022 at the Sally Rock sampling location express average dissolved oxygen concentrations that remain above the state mandated threshold of 4.8mg/l. Additionally, the Sally Rock sampling location has greater average near bottom dissolved oxygen concentrations during the months of July and August with many years never reaching below 4 mg/l. Again, this is not the case at the Greenwich Bay sampling location where near bottom dissolved oxygen contractions for the months of July and August are rarely ever greater than 4 mg/l. This suggests that based on near bottom dissolved oxygen concentrations the Sally Rock sampling location experiences improved water quality parameters. Especially elevated concentrations of dissolved oxygen, a smaller number of algal blooms, a decrease in the amount of nitrogen loading, and potentially a higher rate of flushing.

Environmental drivers:

Greenwich Bay exhibits locations in which pollutants are at higher concentrations than others, as well as areas where water quality is being degraded more than others. Excessive nutrients are transported through these environmental drivers, nutrients express themselves in Greenwich Bay as an increase in hypoxic water conditions and in turn low concentrations of dissolved oxygen. Two of the most prevalent environmental drivers used were precipitation and river flow. When pinned against each other at the yearly scale average Hunt River flow had a strong positive association with average precipitation *(r=.857, p=<.001)* furthermore, this result was statistically significant (*p value <.05).* A visual depiction of this relationship between Hunt River flow and precipitation are depicted in appendix figure 2. This result is crucial because the Hunt River is adjacent to the Greenwich Bay watershed and the use of river flow data needs to accurately represent trends within the watershed. The association between river flow and precipitation is evidence that these two environmental drivers are connected and can be used with other parameters. To determine the effect that runoff has on the water quality of Greenwich Bay, I conducted statistical tests on data which includes flow from the nearby Hunt River, and ambient water quality data overtime. Data from the Hunt River was utilized in this study. The Hunt River flows into the Potowomut and then to Narragansett Bay. Hunt River was used as a surrogate for the tributaries that flow into Greenwich Bay because it is the only river in the area that has consistent long term flow monitoring data. Other tributaries that directly flow into

Greenwich Bay do not have this kind of monitoring effort. The Hunt and Potowomut rivers can be seen in figure 1. The first test was a Pearson correlation test between Monthly average river flow data from the Hunt River and near bottom dissolved oxygen concentrations which were collected from the Greenwich Bay sampling location, as depicted in the blue diamond in figure 6. Monthly (May to October) average Hunt River Flow has a weak positive association with an increased number of monthly (May to October) average bottom DO value per month *(r= .229, p=.022)* This statistically significant result *(p value <.05)* shows that the null hypothesis which states that the relationship between these two variables is up to chance or random order, can be rejected. Alternatively saying that the alternative hypothesis is confirmed, this states that there is a relationship between these two variables, and it is not up to chance in how they are related to one another. As monthly average river flow from the Hunt River increases, the near bottom dissolved oxygen concentrations measured at the Greenwich Bay sampling location also increase, this is known as a positive correlation or positive relationship where one variable increases the other also increases. An increase in near bottom dissolved oxygen is productive, due to a higher concentration of oxygen at depth which allows for wildlife to thrive. The correlation between these two variables is weak in nature, although there is an increase in near bottom dissolved oxygen concentration as river flow increases there could be other variables that cause dissolved oxygen to increase as river flow increases. The Hunt River additionally is not geographically close in relation to the Greenwich Bay sampling location, so as Hunt River flow increases it does not have a direct impact on the hydrological parameters of the Greenwich Bay sampling location.

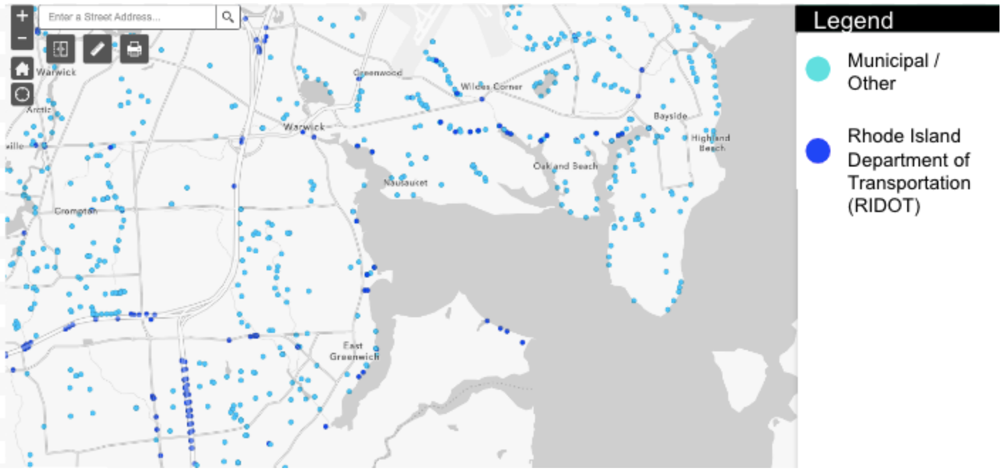


Figure 5: Stormwater outfall locations

Outfall pipes are managed by Warwick, East Greenwich, or the Rhode Island Department of Transportation (RIDOT). Source: RI DEM, Office of Water Resources.

Another example of environmental drivers having an impact on the water quality of Greenwich Bay is in the Pearson correlation test between yearly average Hunt River flow vs the number of hypoxic days measured from May to October by year measured at the Greenwich Bay sampling location from the years 2005 to 2022. Yearly average Hunt River Flow was strongly associated with an increased number of hypoxic days by year *(r= .591, p=.010)* This result is statistically significant (p value <.05) which suggests that we can reject the conclusion that the relationship between these two variables is up to chance or random order. Additionally, this result shows a strong positive association between the two variables which entails that when Hunt River flow increases, the number of hypoxic days observed at the Greenwich Bay sampling location also increases. This indicates that increasing flow from adjacent rivers into Greenwich Bay (which were not measured like the Hunt River data shown) has a negative effect on the water quality at the Greenwich Bay sampling location.

Another Pearson correlation test was conducted to determine which environmental drivers have the strongest impact on the water quality of Greenwich Bay waters is the average May to October precipitation per year vs the number of hypoxic days measured from May to October by year measured at the Greenwich Bay sampling location from the years 2005 to 2022, the results of this test are evident in appendix figure 4. The result of this test shows that average precipitation per year measured at the NOAA precipitation monitoring station as seen in figure 1 was strongly associated with an increased number of hypoxic days per year. *(r= .74. P=<.001)* This statistically significant result (p value <.05) proves the rejection of a null hypothesis in which there is a relationship between two variables and that the result is not because of chance or random order. There is a positive correlation also known as a positive relationship between the two variables, this entails that as precipitation values at TF Green International Airport increase the number of hypoxic days per year also increases. This proves that precipitation has a strong association with the water quality of Greenwich Bay in which greater average precipitation values lead to lower water quality parameters such as the number of hypoxic days. Greater average precipitation values mean that a higher amount of untreated stormwater runoff is being introduced to the bay through stormwater outfalls as well as through tributaries which are areas where stormwater naturally collects and deposits into Greenwich Bay. Stormwater runoff appears to have a direct tie to the number and frequency of hypoxic events in Greenwich Bay.

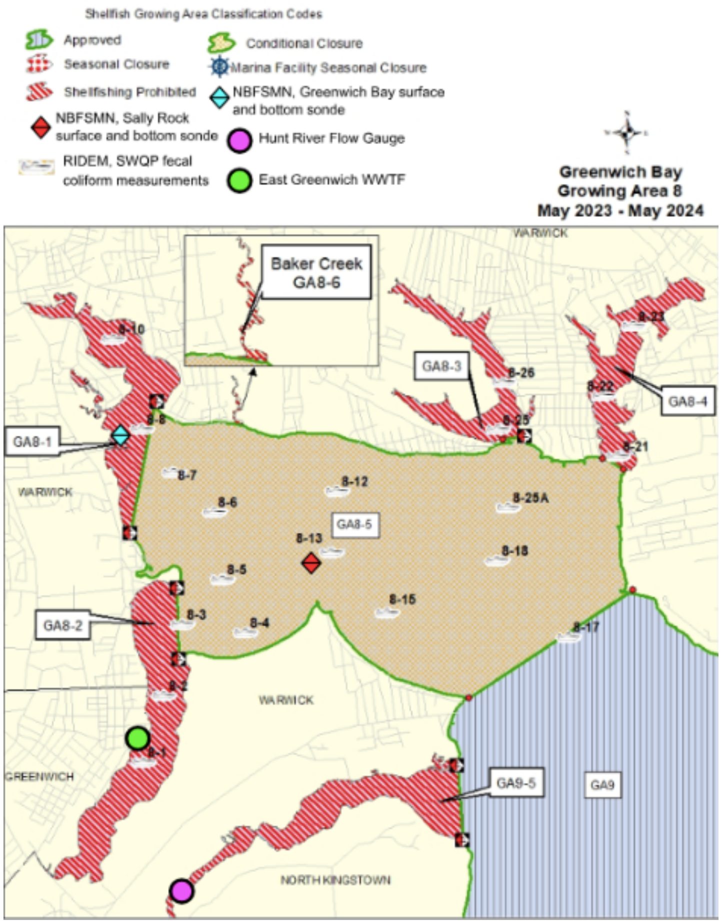


Figure 6: Sampling locations for fecal coliform in Greenwich Bay

Boat shaped makers are locations representing fecal coliform measurements that were taken on a monthly or bimonthly basis from 2005-2023. Blue and red diamonds are the sampling sites for the Narragansett Bay Fixed-Site Monitoring Network (NBFSMN) where data are collected at near surface and near bottom depths. Data is collected year-round from 2005-2023 at the blue diamond, and from May to October from 2008-2022 at the red diamond. The pink circle represents the Hunt River flow monitoring location. Finally, the East Greenwich Wastewater Treatment Facility (WWTF) is depicted by a green circle. Data sources: RI DEM, Office of Water Resources, Shellfish Water Quality Program, and Narragansett Bay Fixed-Site Monitoring Network (NBFSMN).

The final Pearson correlation test conducted was between the average yearly precipitation per May to October vs the # of RIDOCS days (number of hypoxic days) at the Sally Rock sampling location, this test covered the years 2008 to 2022. The results of this test show that average precipitation per year was strongly associated with an increased number of hypoxic days per year. *(r=.71. P=.003)* This statistically significant result (p value <.05) proves the rejection of a null hypothesis in which there is a relationship between two variables and that the result is not because of chance or random order. There is a strong positive relationship between these two variables in which as precipitation values at TF Green International Airport increase the number of hypoxic days per year also increases. A visual depiction of this association between these two variables is depicted in appendix figure 1.

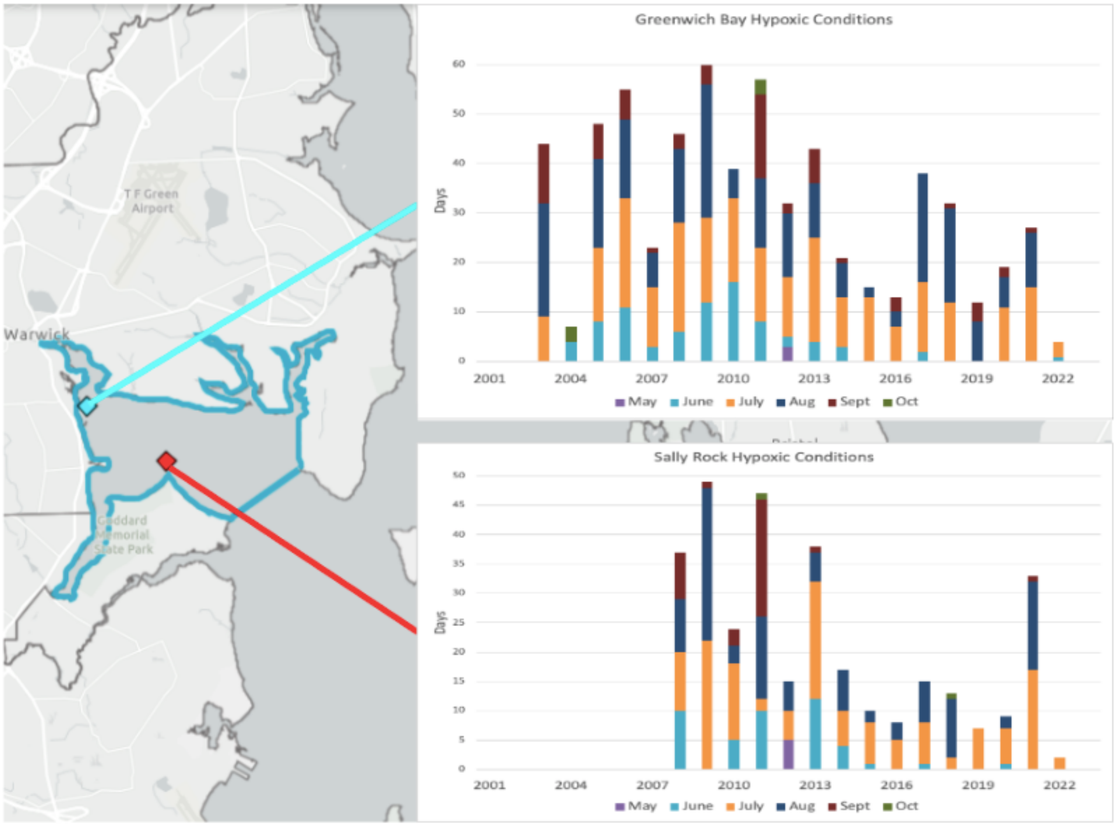


Figure 7: Hypoxic events in Greenwich Bay

Annual near bottom hypoxic occurrences are measured following state regulations. See text for explanation of units. Data is collected from 2003-2022 for the Greenwich site and from 2008-2022 for the Sally Rock site. After 2009 a gradual decline in hypoxia has been observed at both sampling sites. Data source: Narragansett Bay Fixed-Site Monitoring Network (NBFSMN).

The final two statistical tests that were conducted to determine which environmental drivers impact the water quality of Greenwich Bay most were two linear regression analyses using three variables. Average May to October precipitation per year was analyzed against the number of hypoxic days measured from May to October by year measured at both the Greenwich Bay and Sally Rock sampling locations. The Greenwich Bay location utilized data from the years 2005 to 2022; while the Sally Rock Sampling location utilized data from 2008 to 2022. A linear regression is used to predict the value of a variable based on the value of another variable. This is done using an independent and dependent variable. The variable that is predicted is called the dependent variable while the variable that is used to predict the dependent variable's value is the independent variable. In this case the number of hypoxic days is the dependent variable and average precipitation, and river flow are the independent variables. These two independent variables are used to determine the value of the number of hypoxic days. After covariate adjustment, by holding river flow constant at 0 cubic feet per second higher precipitation is associated with a greater number of hypoxic days *(B=10.597, P=.005)* This entails that when precipitation increases by 1 unit (1 inch) the number of hypoxic days at the Greenwich Bay sampling location increase by approximately 10.59 days. The result from this test is statistically significant with a p value of .005 (p value <.05) this shows that the result is not up to chance or random order. Similarly at the Sally Rock Sampling location, after covariate adjustment, by holding river flow constant higher precipitation is associated with a greater number of hypoxic days. *(B=11.82, P=.008)* When precipitation increases by 1 unit (1 inch) the number of hypoxic days increases by approximately 11.82 days. This is a statistically significant finding (p value <.05), meaning these results are a real association and not likely due to random error variation. Based on these results, there is a stronger association between average precipitation and hypoxic days; river flow does not impact the number of hypoxic days as much as precipitation at both sampling locations within Greenwich Bay. This proves that rain events and greater amounts of precipitation are a stronger environmental driver for a higher number of hypoxic events in Greenwich Bay.

A linear regression analysis was used to determine the association between the yearly average May to October number of hypoxic days at the Greenwich Bay sampling location. The Greenwich Bay sampling location can be seen in figure 6 labeled with a blue diamond which is in close relation to Apponaug Cove. The number of hypoxic days at the Greenwich Bay sampling location can also be seen in figure 7. The number of hypoxic days were compared to yearly average May to October precipitation measures from the nearby T.F. Greene International Airport. This linear regression analysis was conducted due to the statistically significant, and strong positive correlation findings from Pearson correlation tests using these two variables. It is hypothesized that an increase in precipitation will lead to an increased number of hypoxic days within Greenwich Bay, but there are a variety of other factors that influence the development, strength, and length of hypoxic days. To narrow in the analysis of hypoxic days and precipitation in Greenwich Bay a series of covariates were used within the linear regression; these covariates were all yearly averages from May to October.

Covariates included maximum air temperature, near surface and near bottom water temperature, near surface and near bottom chlorophyll, and finally stratification values. These covariates were chosen because of their significance in other studies that aimed to understand the trends and drivers of hypoxic conditions in Greenwich or Narragansett Bay overtime. In one study conducted by Codiga et al, their study design focused on understanding eutrophication driven hypoxia in Narragansett Bay. To achieve this, analysis was completed using measurements of dissolved oxygen, chlorophyll, water temperature, as well as influencing factors such as nitrogen load, river flow, salinity, and stratification (Codiga et al, 2020). Air temperature, near surface, and near bottom water temperatures were chosen because of the link between hypoxic conditions and increased summer temperatures. As air temperatures warm, so does surface and bottom temperatures, especially during the spring and summer months which is when hypoxia is most prevalent in Greenwich Bay. As temperatures increase the metabolic rates of chlorophyl and bacteria also increase which leads to higher oxygen consumption, therefore exacerbating hypoxic conditions (Codiga et al, 2020). Air temperatures specifically have been cited to play a role in either providing favorable conditions in which algal blooms can develop and persist or can disrupt the process by mixing and oxygenating the water (Rhode Island Department of Environmental Management, 2003). Measures of near surface and near bottom Chlorophyl are another important factor when it comes to determining the driving forces behind hypoxic conditions in Greenwich Bay. Alternative studies have proved that chlorophyll-a is the most popular indicator of agal concentrations and nutrient over enrichment; chlorophyll-a is related to diurnal dissolved oxygen depressions which is due to algal respiration (Environmental Protection Agency, Office of Water, 2012). It is also established that excessive concentrations of phytoplankton which is indicated by levels of chlorophyll-a can cause adverse impacts to the concentration of dissolved oxygen. Adverse impacts include the depletion of near bottom dissolved oxygen, also known as hypoxic conditions through the decomposition of dead algae (Environmental Protection Agency, Office of Water, 2012). The final covariate used was stratification which is a measure of the density differences between the surface and bottom waters; density differences occur in Narragansett Bay when there are temperature and salinity differences between the surface and bottom waters (Stoffel, Kiernan, 2009). Stratification is critical to the development and intensity of hypoxic conditions as the greater the density difference between the surface and bottom waters (increased stratification value) the harder it is for oxygen to reach bottom waters (Stoffel, Kiernan, 2009). Therefor as stratification increases so does the number of hypoxic conditions at near bottom depth. Previous studies have also determined that there is a strong link between stratification and the intensity and duration of hypoxic events in Narragansett Bay; finding that the years with the highest number of hypoxic events correlated with the years with the most intense stratification (Stoffel, Kiernan, 2009). Stratification was calculated using measures from both the near surface and near bottom sondes at the Greenwich Bay and Sally Rock sampling locations labeled as a blue and red diamond in figure 6. Stratification was measured in (kg/m3) by determining the near surface and near bottom density of saltwater, then taking the difference of these two densities over time.

The density of saltwater was calculated using the equation of state, by taking temperature in Celsius, salinity in parts per thousand (PPT) and depth in meters. Covariates are parameters that influence the dependent variable, so covariates are held constant to determine the association between the predictor variable (independent variable) and the dependent variable. The predictor or independent variable in this linear regression is precipitation values while the dependent variable is the number of hypoxic days. After covariate adjustment higher precipitation is associated with a greater number of hypoxic days *(B=10.71, P=.04)*. When precipitation increases by 1 unit (1 inch) the number of hypoxic days increases by approximately 10.71 days. These findings are statistically significant meaning these results are a real association and not likely due to random error variation. Both the results depicted within the Pearson correlation test as well as this linear regression prove that precipitation plays a strong role in the development of hypoxic days at the Greenwich Bay sampling location. The use of covariates in this analysis further proves that other factors which have a pivotal role in the creation of hypoxic estuarine conditions do not affect hypoxic conditions as strongly as precipitation does. This shows the connection between untreated stormwater runoff and the development of hypoxic water conditions within the Greenwich Bay watershed, especially near Apponaug Cove as this is where the Greenwich Bay sampling location is located.

Figure 8: Greenwich Bay hypoxic events with precipitation.

The number of hypoxic events is monitored during the months of May to October. Monthly total precipitation was recorded at T.F. Green Airport. The standard deviation of precipitation and number of hypoxic events were used to calculate error bars. Data sources: Narragansett Bay Fixed-Site Monitoring Network (NBFSMN) and NOAA National Centers for Environmental Information.

The final linear regression analysis conducted to determine how environmental factors impact hypoxia in Greenwich Bay was an analysis of monthly May to October average near bottom dissolved oxygen concentrations versus monthly average May to October Hunt River flow. This data spanned the years of 2005-2021 and utilized data collected from the Greenwich Bay sampling location. Dissolved oxygen data was collected from the Narragansett Bay Fixed-Site Monitoring Network (NBFSMN), measures were taken at near bottom depths at 15-minute intervals. These measures were averaged together to obtain monthly average near bottom concentration of dissolved oxygen at the Greenwich Bay sampling location. Hunt river flow was obtained in cubic feet per second from the US Geological Services (USGS), this information was utilized to achieve monthly average flow rates. This linear regression was conducted due to the results determined in previous Pearson correlation tests which determined that there was a weak positive correlation between monthly average river flow and monthly average near bottom dissolved oxygen concentrations at the Greenwich Bay sampling location. It is hypothesized that an increase in river flow will result in a decrease in the concentration of near bottom dissolved oxygen; river flow introduces nonpoint sources of pollution like nutrients which prompt hypoxic events therefore decreasing the concentration of near bottom dissolved oxygen. Covariates include monthly average: maximum air temperature, water temperature, both surface and near bottom chlorophyll measures, and finally stratification. Covariates are parameters that influence the dependent variable, so covariates are held constant to determine the association between the predictor variable (independent variable) and the dependent variable. The predictor or independent variable in this linear regression is river flow values while the dependent variable is the concentration of near bottom dissolved oxygen values. After covariate adjustment higher river flow is associated with a decrease in the concentration of near bottom dissolved oxygen *(B= -.013, P.003)*. When river flow increases by 1 cubic foot per second the concentration of near bottom dissolved oxygen decreases by approximately .013 mg/l. This linear regression analysis resulted in statistically significant results (p value <.05), meaning these results are a real association and not likely due to random error variation. This linear regression analysis proves that river flow plays a role in the decrease in concentration of near bottom dissolved oxygen value at the Greenwich Bay sampling location. This same linear regression analysis was conducted using dissolved oxygen data and covariate data from the Sally Rock sampling location. This analysis proved statistically insignificant results with little to no correlation between the independent and dependent variables. River flow disproportionately affects specific areas of Greenwich Bay over other areas. It is critical to clarify that the Hunt River does not directly flow into Greenwich Bay proper where both the Greenwich Bay and Sally Rock sampling locations are located. Hunt River is utilized in this study because it is the only river within the area that has continuous and long-term flow monitoring efforts.

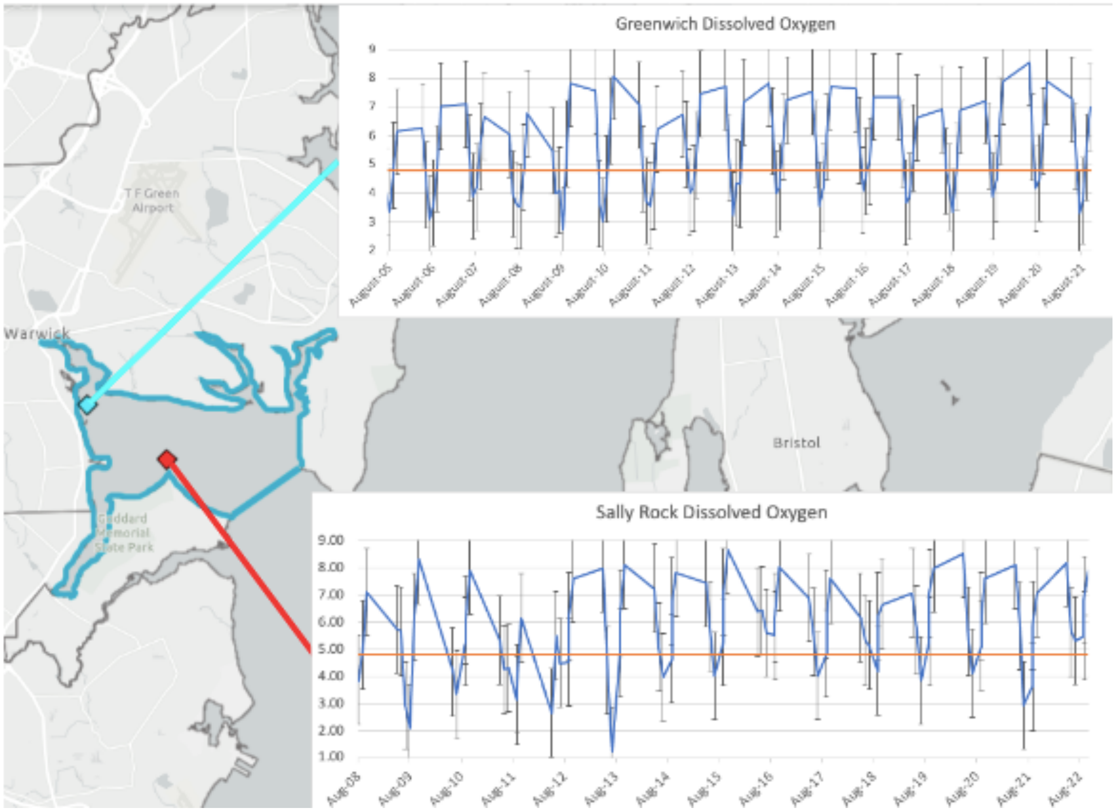


Figure 9: Near bottom dissolved oxygen in Greenwich Bay

Data was collected exclusively for the months of May to October and shows the frequency of low oxygen events at each site. Greenwich site is near Apponaug Cove which exhibits consistent low dissolved oxygen in July and August, all of which exceed the state mandated limit of 4.8 mg/l. The Sally Rock site appears to have overall higher concentrations of dissolved oxygen especially after 2013. The standard deviation was used to calculate error bars for dissolved oxygen data. Data source: Narragansett Bay Fixed-Site Monitoring Network (NBFSMN)

Discussion

The results found through the course of this study can be broken down into observation-based results and significant results based on statistical analysis. Observation based results are takeaways from raw data that give insight on the distribution and intensity of pollutants in different areas of Greenwich Bay and what anthropogenic actions could be causing the changes. Significant results are the conclusions that can be drawn from the use of either Pearson correlation, or linear regression analysis that were completed for a variety of different parameters. The two main pollutants or outcomes to anthropogenic change in the Greenwich Bay watershed are concentrations of fecal coliform that are unfit for human interaction either through shellfishing or swimming, and secondly low concentrations of near bottom dissolved oxygen which are known as hypoxic conditions. Results will be split up by these two major impacts on the Greenwich Bay watershed to cover the findings in this research.

Fecal coliform:

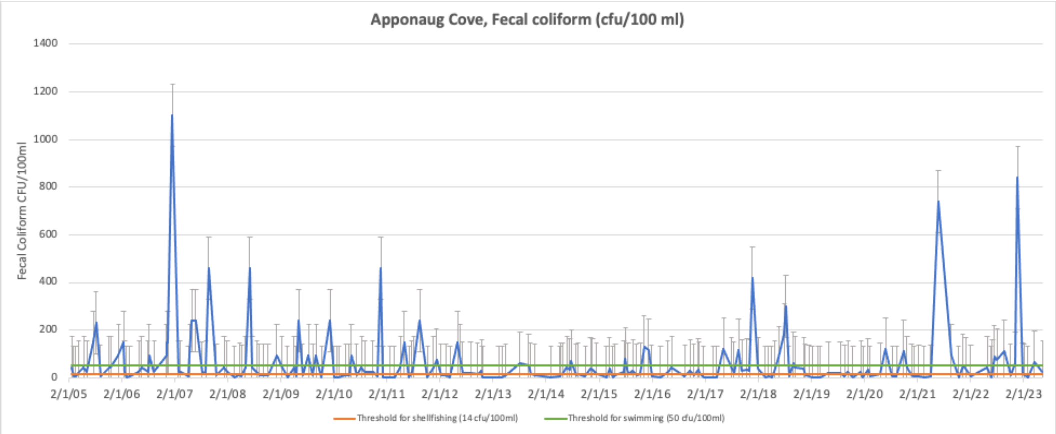
Based on observations within this study, especially figure 4, table 2, and 3 determine that fecal coliform is one of the most detrimental environmental impacts caused by anthropogenic use of the Greenwich Bay watershed. The observations derived from tables 2, and 3 show that there are instances where fecal coliform exceeds state mandated criteria for swimming and especially shellfishing at nearly every single sampling location. These exceedances directly violate both state and federal legislation surrounding the management of water quality in Greenwich Bay as well as interfere with both commercial and recreational stakeholder groups. These observations are further supported by studies conducted within the Greenwich Bay watershed, as well as national studies on the effects of fecal coliform on estuary systems. Fecal coliforms are considered primary bacterial indicators for the presence of human pathogens in waters; exposure to these harmful microorganisms through swimming and boating can cause health impacts such as gastroenteritis, sore throats, meningitis, or encephalitis (Narragansett Bay Estuary Program, 2017). Additionally, the EPA has cited that fecal pathogen are implicated as the leading cause of water quality impairment in the US (USEPA 2016). This proves that fecal coliform within both the Greenwich Bay watershed and national waters of the US are a major issue and something that needs to be addressed.

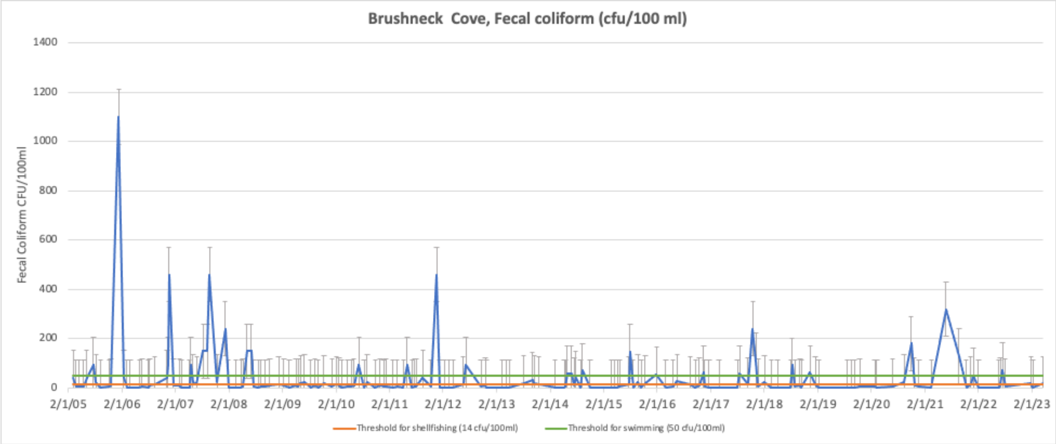
Based on observations derived from figure 4, areas of highest concentration for fecal coliform are in the northernmost embayment’s, these being Apponaug Cove, Brushneck Cove, and finally Warwick Cove. This observation confirms that the East Greenwich WWTF, which is in Greenwich Cove, the southernmost embayment is not a significant contribution to the fecal coliform in Greenwich Bay. This observation is confirmed by studies conducted in the area regarding shellfishing in Greenwich Bay, “The facility is permitted to discharge a maximum daily of 1.70 MGD (million gallons/day) of treated effluent. The average flow for 2021 was 0.87 MGD, well within the permit limits. While fecal coliform is not a permit criterion, it is monitored, and average monthly geometric mean fecal coliform was 5.4 cfu/100 ml during 2021”

(Rhode Island Department of Environmental Management, 2021). According to the East Greenwich WWTF permit, fecal coliform is a form of effluent that must be monitored, and data needs to be reported but no limit has been established within said permit. The permit mandates that monitoring for fecal coliform shall be conducted every three weeks through grab samples (Rhode Island Department of Environmental Management, 2017). Due to shellfishing being prohibited within Greenwich Cove indicates that the location and discharge rate of the East Greenwich WWTF allows for ample dilution of effluent before theses water enter the conditionally closed shellfishing area as evident in figure 2. Having areas of Greenwich Bay where shellfishing is prohibited is necessary as a method for diluting pollutants that enter Greenwich Bay through both nonpoint source and point sources. This conclusion is supported by the Rhode Island Department of Environmental Management in their assessment of shellfishing designations of Greenwich Bay. This conclusion made by the Rhode Island Department of Environmental Management further supports the need for policy alternatives surrounding management of water quality in the Greenwich Bay watershed. Through a thorough review by the Rhode Island Department of Environmental Management of the East Greenwich WWTF, it further confirms that the facility is well run, operating well below permitted bacteria discharge levels, and not a significant source of fecal coliform into Greenwich Bay (Rhode Island Department of Environmental Management, 2021). By confirming that the East Greenwich WWTF is not a significant source of contamination to Greenwich Bay it insinuates that alternative anthropogenic actions are the driving force behind fecal coliform entering Greenwich Bay.

A series of statistical tests were conducted surrounding concentrations of fecal coliform within the Greenwich Bay watershed pertaining to different vectors that could be responsible for the introduction of fecal coliform. Pearson correlation tests were used to determine the correlation between concentrations of fecal coliform across Greenwich Bay and both precipitation and flow in a river adjacent to the Bay. It is hypothesized that higher amounts of precipitation are correlated with an increase in concentration of fecal coliform. Furthermore, untreated stormwater runoff carries pathogens like fecal coliform from pet waste or more significantly from outdated, leaking individual septic systems located near the Greenwich Bay coastline. To test this hypothesis precipitation measurements were taken daily at a monitoring station located at the T.F. Green international airport which is in the Greenwich Bay watershed. Precipitation measurements include both rain and snow and monthly sums were utilized to determine the total amount of precipitation that occurred on a monthly or yearly basis. Fecal coliform measurements were taken on a monthly or twice monthly basis by the Rhode Island Department of Environmental Management Office of Water Resources, Shellfish Water Quality Program. Samples were taken across 20 different locations as seen in figure 6. Both datasets were utilized in a series of statistical tests that used Pearson correlation to determine the association between these two variables overtime. Tests include yearly average precipitation versus yearly average fecal coliform values across all sampling locations, and yearly average precipitation versus yearly average fecal coliform values strictly using data from sites 10, 26, and 22 as these were the three sampling locations that had the highest concentration of fecal coliform over the entire time series. Both statistical tests resulted in statistically insignificant results and there was little to no correlation between the variables. The hypothesis depicted above was not supported by these Pearson Correlation tests; precipitation was not correlated with an increase in concentration of fecal coliform. This association leads me to speculate that fecal coliform is likely entering Greenwich Bay through groundwater sources which results in a delayed response in terms of when fecal coliform is present in sampling efforts. Due to this lag, there in a lack of association between fecal coliform and precipitation measures.

The results from these statistical analyses did not reflect the findings of other studies that utilized similar datasets to prove the relationship between precipitation and concentrations of fecal coliform within the Greenwich Bay watershed. In a similar study conducted by the Rhode Island Department of Environmental Management Shellfish Program, known as the Shellfish Growing Area Monitoring (SGAM) program a series of wet weather fecal coliform samples were collected during June 2021 at boat shaped symbols in figure 6. Samples were collected half a day after 1.05 inches of rain occurred in the area. 19 of 20 samples or 95% of these samples exceeded fecal coliform concentrations of 14 cfu/100 ml. Precipitation values were collected from a weather station at the T.F. Greene International Airport, this is the same location in which precipitation values were collected for this study. This indicates that after 1 inch of precipitation in the Greenwich Bay watershed the water quality of certain areas is unfit for shellfishing, as stated in the state mandated threshold (Rhode Island Department of Environmental Management, 2021). Additionally, this study indicates that the current procedure in place regarding the conditional closure of shellfishing in Greenwich Bay is appropriate and should remain in place. The current procedure (Rhode Island Department of Environmental Management) states that when half an inch or more of rain occurs within the watershed it causes a seven-day closure to all shellfishing activities within conditionally closed areas as seen in figure 2. This study proved that there is a strong correlation between an increase in precipitation and an increase in the concentration of fecal coliform that enters the Greenwich Bay estuary system. Alternative studies like in the RIDEM SGAM program will often exclusively use "wet weather" data which uses samples that have been taken after a set amount of precipitation occurs. The use of "wet weather" samples excludes times when rain events do not occur, as well as only including a smaller time frame by only having sampling events when rain events occur. The alternative study depicted above exclusively took samples during the month of June for the year of 2021, this extremely short sampling window is a drastic change from the time frame utilized in this study. The data utilized in my Pearson correlation analysis utilized yearly average concentrations of fecal coliform taken on a monthly or twice monthly basis during both dry and wet weather events. A visual representation of this lack of association is evident in appendix figure 3 which depicts a minimal slope between the two variables. I suspect that including both dry and wet weather events across a longer time frame is the reason why there are inconsistencies between the results found in alternative studies and the results depicted in this study. I anticipate that narrowing in my sample window to include only wet weather samples during a month-long period and utilizing actual fecal coliform measurements rather than averages could lead to results that are like those that found associations between precipitation and fecal coliform in Greenwich Bay. Alternative studies like the one depicted above cannot accurately depict long term associations between elevated concentrations of fecal coliform and precipitation events over time. By utilizing samples strictly from June of 2021 researchers can highlight the association between elevated concentrations of fecal coliform and precipitation events at one point in time which is beneficial in understanding the status. This methodology gives little to no insight in understanding the long-term changes in concentrations of fecal coliform overtime. There this study would need to be completed year after year to truly understand the long-term effects precipitation has on the concentration of fecal coliform in Greenwich Bay.


Apponaug Cove, Fecal coliform (cfu/100 ml)


Brushneck Cove, Fecal coliform (cfu/100 ml)

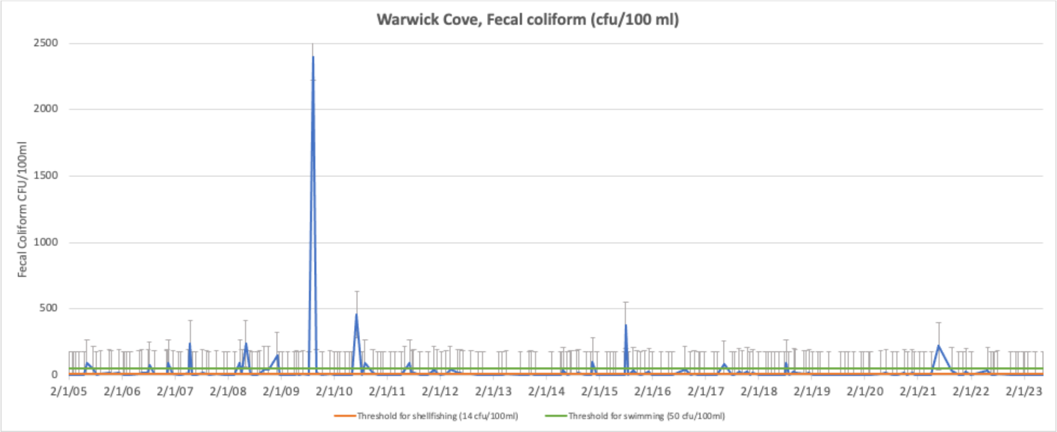


Figure 10: Fecal coliform trends in Northern embayments.
Monthly fecal coliform measurements are taken from February 2005 to June 2023. Two thresholds are fitted to the figure; these thresholds are 14 cfu/100ml for safe shellfishing, and 50 cfu/100ml for safe swimming. Apponaug Cove has the greatest number of samples that exceed both thresholds and exceedances occur as recently as 2023. Brushneck and Warwick cove have a smaller number of samples that exceed these thresholds with most of these exceedances occurring before 2012. Error bars are calculated with the use of the standard deviation of fecal coliform data. Data source: RI DEM, Office of Water Resources, Shellfish Water Quality Program.

Another hypothesis surrounding fecal coliform entering Greenwich Bay is through freshwater rivers and tributaries within the Greenwich Bay watershed. Similarly, to precipitation, it is believed that as river flow increases so does the concentration of fecal coliform. Failing individual septic systems in close relation to these rivers and tributaries are believed to be the most impactful source of fecal coliform into freshwater rivers. These rivers collect fecal coliform overtime, especially during precipitation events which is why it is believed that river flow is tied to higher concentrations of fecal coliform in Greenwich Bay. To test this hypothesis, a series of Pearson correlation tests were utilized to determine the correlation between river flow and concentration of fecal coliform within the Greenwich Bay watershed. Long term river flow was utilized from the Hunt River which does not directly flow into Greenwich Bay, or into areas where fecal coliform concentration measurements were taken. The results derived from these Pearson correlation tests did not support the hypothesis provided above. Results did not provide statistically significant results, and there was very weak to no correlation between variables. Other studies that specifically investigated the tributaries that flow into Greenwich Bay found that river flow and freshwater input were drivers of increased concentrations of fecal coliform within the watershed. One study conducted by the Federal Drug Administration (FDA) identified Hardig Brook within Apponaug Cove as the largest wet and dry weather source of fecal coliform into the Greenwich Bay watershed (Rhode Island Department of Environmental Management, 2005). This FDA study of 1993 similarly found that Apponaug Cove had the highest concentration of fecal coliform out of the entire watershed, especially under wet weather conditions. This follows my observations based on the spatial distribution of fecal coliform within the watershed with Appanoug being the site with the highest concentration of fecal coliform. The FDA reported that 95% of the overall daily, and 99% of the wet weather inputs of fecal coliform into the watershed came from sources which included Hardig Brook, Southern Creek, and the Maskerchugg River (Pesch et al. 2012). All three of these sources of freshwater input into Greenwich Bay flow into shallow embayment; this follows suit with the results derived from my observations that shallow embayment's with an abundance of freshwater inputs are areas where fecal coliform concentrations are the highest. The results from this FDA study prove that freshwater inputs into Greenwich Bay are a significant contributor to the increase in concentrations of fecal coliform, especially within the northern embayment's which express higher concentrations of fecal coliform during wet weather events as well as increased river flow. River flow data from the rivers depicted in the FDA study are not up to date or measured on a long-term time series like the Hunt River. This lack of river flow data from Hardig Brook, Tucatucket Brook, and the Maskerchugg river could be the reason why there was a lack in statistically significant correlations between Hunt River flow and Greenwich Bay fecal coliform concentrations.

The tributaries and embayments within the northern reaches of Greenwich Bay are encompassed by the city of Warwick Rhode Island while southern embayments are within the Town of East Greenwich Rhode Island. Both suburban areas impact the water quality of Greenwich Bay, and both areas utilize OWTS (Onsite Wastewater Treatment System) as well as municipal sewer systems that connect to either the East Greenwich WWTF for the residents of East Greenwich or the City of Warwick WWTF for the residents of Warwick. Based on the population of individuals in both East Greenwich and Warwick, census population statistics, and the number of current OWTS permits in use we can estimate the number of individuals who are not tied into municipal sewer systems. The 2010 census population estimate for East Greenwich RI is 13,146 people, the estimated population served by sewers according to the East Greenwich WWTF is 6,000 individuals. This alone shows the imbalance between the number of individuals who reside in East Greenwich and the number of people who can be supported by the East Greenwich WWTF. The Rhode Island Department of Environmental Management (RI DEM) also accounts for all current active OWTS permits in East Greenwich; there are 3,307 permits in use. This number of permits does not reflect the number of people who are supported by septic systems because clearly multiple people can live in the same household and be supported by one OWTS system. Regardless, there is clearly an imbalance between the number of individuals in the Town of East Greenwich and the number of people who can be supported by the East Greenwich WWTF. This imbalance highlights the need for further sewer extensions as well as the continuation of homes to tie into municipal sewer systems which would eliminate the need to use OWTS.

The city of Warwick Rhode Island is serviced by the City of Warwick WWTF, which does not discharge its effluent into Greenwich Bay. The city of Warwick also utilizes OWTS which are near Greenwich Bay and its tributaries. It is critical to understand the number of OWTS in the city of Warwick because these OWTS contribute to the quantity of both nitrogen and fecal coliform that enter the Greenwich Bay watershed. According to most recent projections, the Warwick Sewer Authority (WSA) provides sewer services to 26,178 properties within the City of Warwick, out of those properties 23,642 are currently connected to the municipal sewer system which utilizes the City of Warwick WWTF (Poole, 2024). This entails those 2,536 properties are serviced by OWTS within the City of Warwick. Like in the case with East Greenwich, there is a clear imbalance between the population of Warwick and the number of individuals who are serviced by municipal sewer systems. This reliance on OWTS contributed to the introduction of both nitrogen and fecal coliform into the Greenwich Bay watershed. The WSA is aware of the environmental impacts associated with

OWTS, which is why the WSA has spearheaded the expansion of municipal sewer systems throughout the City of Warwick to mitigate the use of OWTS which are a source of pathogens like fecal coliform into both Greenwich and Narragansett Bay. The WSA is currently expanding municipal sewers through their Bayside sewer project, this project aims to allow 935 homes to be able to connect to municipal sewer lines (Poole, 2024). This project area is in closer proximity to Narragansett Bay rather than Greenwich Bay but limiting the use of OWTS around the Greenwich Bay watershed is a vital step to reduce the influx of nutrients and fecal coliform from entering both Greenwich and the greater Narragansett Bay. The Bayside sewer project is expected to be completed in the fall of 2024 with construction efforts resuming April 1st of 2024. There are some areas within the Greenwich Bay watershed that still do not have access to municipal sewer lines; these locations rely on OWTS as their only option. An example of this is Pottowomut which is a community on the south side of Greenwich Bay, near Greenwich Cove. In this area due to the prevalence of bedrock which makes the installation of sewer lines difficult. Specifically looking at areas around Greenwich Bay there are 2,059 properties connected to municipal sewer lines with 213 properties that have access to sewer lines but are not connected (Poole, 2024). These 213 properties rely on OWTS and one of those properties is the Buttonwoods Campground which encompasses 119 cabins all of which utilize OWTS (Poole, 2024). Along with sewer expansions, the WSA is responsible for the implementation of a mandatory connection program that requires developed parcels of land with access to municipal sewer lines to tie-in within one year of notification (Warwick Sewer Authority, 2007). This mandatory tie-in initiative is only possible if municipal sewer lines are extended to accommodate homes and businesses to utilize said sewer lines. Sewer extensions have occurred. Residents within the City of Warwick are mandated to tie into municipal sewer lines if their OWTS or septic system fails, if the property is sold or transfers ownership, or if the cesspool is within 200 ft of a coastal feature, drinking well, or other body of water. Residents are therefore not required to tie into municipal sewer lines if their OWTS system is functioning properly (Warwick Sewer Authority, 2024). Homes within 200 feet of coastal features and other bodies of water is a direct management effort that targets the influx of fecal coliform and nutrients from entering Greenwich Bay. Unfortunately, groundwater and surface water transport through precipitation can still act as a vector of pollutants from OWTS into the Greenwich Bay. Therefore, the complete elimination of OWTS within the Greenwich Bay watershed should be achieved to fully mitigate the negative environmental impacts associated with OWTS.

Hypoxia:

Hypoxia is one of the most detrimental environmental responses to anthropogenic change within the watershed. Hypoxic conditions in Greenwich Bay have been reported for decades and the early 2000s was when hypoxia in Greenwich Bay became a topic of interest for many researchers as well as policy makers. On August 20th, 2003, one of the largest fish kill events occurred in Greenwich Bay which resulted in nearly one million dead fish washing up on beaches or floating on the surface of Greenwich Bay. This fish kill event was the largest in 50 to 100 years and was the most recent large-scale fish kill event experienced in Greenwich Bay (Rhode Island Environmental Monitoring Collaborative, 2024). This fish kill event was caused by extremely low concentrations of dissolved oxygen also known as hypoxic water conditions. Dissolved oxygen readings at the Greenwich Bay Marina dock depicted by a blue diamond in figure 6 showed that the concentration of dissolved oxygen had dropped to zero on the day of the fish kill event. These anoxic conditions extended out to the mouth of Greenwich Bay, nearly covering all of Greenwich Bay as well as covering the entire water column within the Western portions of the Bay (Rhode Island Department of Environmental Management, 2003). Other environmental parameters such as precipitation, ambient air temperatures, water flow, wind direction and speed all played an important role in the formation of these hypoxic conditions. Scientists from the Narragansett Bay Estuary Program and Brown University in other studies proved that high amounts of stormwater runoff and low salinity in surface waters is not required to get hypoxic conditions to occur. Low energy situations through very weak neap tides and low velocities of wind are a driver of hypoxic conditions (Rhode Island Department of Environmental Management, 2003). It is crucial to note that during years with minimal rainfall hypoxic conditions can still occur within the Greenwich Bay watershed, with hypoxic events occurring during wet, dry, and intermediate years when it comes to precipitation. This is due to circulation conditions and the proximity to nutrient loading sources (Codiga, 2020). Circulation conditions are impacted by a variety of different factors, wind speed and direction being one of those factors. According to the Rhode Island Environmental Monitoring Collaborative the year 2003 overall had very high ambient air temperatures, high amounts of precipitation, and low rates of flushing led to low mixing of oxygen into bottom waters (Rhode

Island Environmental Monitoring Collaborative, 2024). Greenwich Bay being a shallow embayment with even more shallow coves leads to poor circulation and flushing, these attributes make Greenwich Bay more susceptible to nutrient loading, algal blooms, and prolonged low oxygen conditions. Weather factors such as wind direction, strength as well as air temperature play a role in the development and intensity of hypoxic events in Greenwich Bay (Rhode Island Department of Environmental Management, 2003). According to the RIDEM the event was caused by significant rainstorms which were followed by a significant bloom of phytoplankton in the shallow areas of the Bay. This bloom was followed by a gradual and then very rapid decline in dissolved oxygen (Rhode Island Department of Environmental Management, 2003). RIDEM personnel believed that this phytoplankton bloom was caused by an increase in nitrogen loading into Greenwich Bay through surface and groundwater flow including from areas served by septic systems. Alternative sources of nitrogen in the Greenwich Bay watershed include effluent from WWTF and septic systems, stormwater runoff, groundwater flow from polluted areas, and discharge from vessels (Rhode Island Department of Environmental Management, 2003). The fish kill event killed juvenile Menhaden, crabs, and American eels; smaller fish kill events occurred weeks prior to the August 20th fish kill and many soft-shell clams died as a result (Rhode Island Environmental Monitoring Collaborative, 2024). Figure 7 highlights the number of hypoxic days experienced at the Greenwich Bay sampling location over time, the year 2003 had 44 hypoxic days and is not the year with the highest number of hypoxic days. According to the state of Rhode Island water quality regulations, hypoxic conditions are deemed to be any concentration of dissolved oxygen that is 4.8 mg/l or lower, this is applied to saltwater which includes Greenwich Bay. Concentrations of dissolved oxygen at 4.8 mg/l or greater are protective of Aquatic Life Uses, in which aquatic organisms are not caused stress. Any dissolved concentration below 4.8 mg/l causes stress to aquatic organisms which is deemed as the first point in which salt waters are hypoxic. Hypoxia is more severe as concentrations of dissolved oxygen decrease past the 4.8 mg/l threshold. Hypoxic days as depicted in figure 7 are a measure of time and do not measure the intensity of hypoxic events, so while 2003 did not have the highest number of hypoxic days the intensity of the fish kill event would not be represent the sheer destructive force of low concentrations of dissolved oxygen in an estuary system like Greenwich Bay. While the 2003 fish kill is one of the largest fish kill events to occur in Greenwich Bay it was not the only fish kill to occur. RIDEM personnel stated that there have been problems with low oxygen levels and fish kills occurring nearly every summer from the early 1990s until the early 2000s in the upper half of Narragansett Bay which includes Greenwich Bay (Rhode Island Department of Environmental Management, 2003). Fish kill events in Greenwich Bay can oftentimes be small, localized events which often go unnoticed but are still due to hypoxic and even anoxic concentrations of dissolved oxygen caused by nutrient flux. In both July of 1998 and 1999 hypoxic and anoxic conditions occurred in Greenwich Bay which resulted in the death of hundreds of fish and other animals; these events extended along the entire western shore, including Greenwich Cove (Rhode Island Department of Environmental Management, 2003). Another example occurred in June of 2001 in which hypoxic and anoxic conditions killed thousands of fish and other animals, especially in Apponaug Cove (Rhode Island Department of Environmental Management, 2003). Clearly the 2003 fish kill event was not an isolated case and smaller less severe fish kill events have been reported in Greenwich Bay before.

These fish kill events have direct impacts on both vulnerable marine species like juvenile and larval fish species as well as rugged species like bivalves. Fish kills are a very extreme result of hypoxic conditions, but even less intense and short windows of hypoxic conditions in Greenwich Bay are extremely impactful to both the ecology and to recreational stakeholders, it is cited that one of the most widespread and deleterious anthropogenic impacts to estuarine and coastal waters is hypoxia or oxygen depletion driven by eutrophication or the reflected in this data. Although the intensity of the 2003 fish kill is not represented in the number of hypoxic days data, overall, the number of hypoxic days for 2003 were significantly higher than the average number of hypoxic days from 2003 to 2022. This suggests that 2003 experienced both an increased number of hypoxic days as well as intense hypoxic events as evident by the August 20th fish kill. Both this study as well as alternative studies in Greenwich Bay conclude that low concentrations of dissolved oxygen or hypoxia are one of the most impactful results of anthropogenic uses and alterations to the landscape surrounding the Greenwich Bay watershed.

After the fish kill of 2003 many regulators set out to ensure that the number of hypoxic days and the intensity of these hypoxic events did not reach the same level as they did during the 2003 fish kill. Regulatory efforts focused on reducing the amount of nutrients, especially nitrogen from entering Greenwich Bay to mitigate the number and severity of hypoxic events. Excessive nutrients especially nitrogen in estuarine systems lead to high productivity and an overgrowth of aquatic vegetation; this overgrowth is known as an algal bloom. As these plants use up the available nitrogen in the water they eventually die off and sink down in the water column. Microbes will then decompose these aquatic plants which stimulate microbe growth; in turn using up most if not all the available dissolved oxygen in bottom waters, therefore causing hypoxia or in extreme cases anoxia (Stoffel, Kiernan, 2009). The Rhode Island General Assembly stepped in and enacted a law directing the Rhode Island Department of Environmental Management (RIDEM) to reduce the nitrogen loading to Narragansett Bay by 50%, this applies to Greenwich Bay as a whole. RIDEM focused nutrient reduction efforts by upgrading 11 wastewater treatment facilities (WWTF) in the upper bay area which includes the East Greenwich WWTF (Rhode Island Environmental Monitoring Collaborative, 2024). These upgrades to WWTFs around Narragansett Bay occurred over several years and were mostly complete by 2012-2013 the results of these upgrades became apparent in 2014 in the form of a “post-reduction” year, where nitrogen levels across Narragansett Bay experienced reductions (Codiga et al, 2020). Another example of nutrient reductions in Narragansett Bay are evident by the difference in nitrogen loading from WWTF between 2003 and 2014; studies found that there was a 65% reduction in nutrient loading from WWTF across Narragansett Bay (Rhode Island Environmental Monitoring Collaborative, 2024). These reductions in nutrient loading into Narragansett Bay are correlated with a smaller number of hypoxic days experienced at many locations in the Bay with Greenwich Bay being one of these locations. An analysis of hypoxic events using the Greenwich Bay data retrieved from the blue diamond in figure 6 proved that in 2017 during intermediate river flow there was not a single hypoxic event at the lowest threshold for hypoxic events at 1.4 mg/L-1; this indicates that nutrient reductions from WWTF upgrades were correlated with a smaller number of hypoxic events within Greenwich Bay (Codiga et al, 2020). These results provided from alternative studies align with the results depicted from figure 7; with a clear "post-reduction" in the number of hypoxic days after 2013 at both the Greenwich Bay and Sally Rock Sampling locations, likely related to nutrient load reductions. Figure 7 also provides insight that the number of hypoxic days at the Sally Rock sampling location are on a gradual decline after 2013 in which WWTF upgrades were completed. The number of hypoxic days at both the Sally Rock and Greenwich Bay sampling location has not exceeded the number of hypoxic days experienced in 2013, this shows that nutrient reductions had a positive effect on the water quality of Greenwich Bay with a reduction in the number of hypoxic days over time.

Hypoxic events in Greenwich Bay follow trends based on determining environmental drivers, the two major drivers are precipitation and river flow. It is hypothesized that an increase in precipitation and river flow will correlate with a larger number of hypoxic days. An increase in both precipitation as well as river flow go hand in hand because an increase in precipitation will result in an increase in freshwater river flow. Both will lead to an increase in the number of nonpoint sources of pollutants as well as contribute to changes in salinity especially in surface waters. Freshwater inputs to Narragansett Bay include contributions from river flow, inputs from WWTFs and precipitation; freshwater flow has been linked to the development of hypoxia (Kellogg, 2018). It is also cited that changes in global and regional patterns in precipitation put stress on ecosystem conditions such as concentration of dissolved oxygen, chlorophyll, and water clarity; precipitation also influences stressor indicators such as wastewater effluent and therefore nutrient loading (Narragansett Bay Estuary Program, 2017). Clearly precipitation impacts a variety of different natural and manmade processes, all of which can negatively impact the water quality of Greenwich Bay. Precipitation having an impact on the number of hypoxic days per year was confirmed in some but not all the examples presented in this study through a series of Pearson correlation tests; precipitation has a strong positive relationship with the number of hypoxic days measured at both the Greenwich Bay and Sally Rock sampling locations. Hunt River flow was moderately associated with an increase in the number of hypoxic days strictly at the Greenwich Bay sampling location; statistically insignificant results were found at the Sally Rock Sampling site using the same parameters. This statistical analysis suggests that as precipitation increases, so does the number of hypoxic days over time at both locations within Greenwich Bay. To further test the effect precipitation has on the number of hypoxic days, two linear regression analyses were conducted to determine if precipitation or river flow has a stronger association with the number of hypoxic days. For the Greenwich Bay and Sally Rock sampling locations there was a stronger association between precipitation and the number of hypoxic days rather than river flow. At the Greenwich Bay sampling location hypoxic days increase by approximately 10 days with every one-inch increase in precipitation. At the Sally Rock Sampling location hypoxic days increase by approximately 11 days with every one-inch increase in precipitation. To take this analysis a step further another set of linear regression analyses were performed to better understand how other environmental factors impact the number of hypoxic days within Greenwich Bay. This was done by analyzing the association between the number of yearly average hypoxic days and yearly average precipitation values by using a series of covariates to better understand how alternative environmental factors impact hypoxia in Greenwich Bay. This analysis concluded that when precipitation increases by 1 inch the number of hypoxic days increases by 10.71 days. This same analysis was conducted utilizing data from the Sally Rock Sampling location. The results proved statistically insignificant and there was no association between the number of hypoxic days and precipitation. This suggests that specific areas of Greenwich Bay are affected differently by different hydrological processes as well as other environmental variables. Precipitation has a strong impact on the water quality in and around the Greenwich Bay sampling location as evident in both this study as well as other studies within the Narragansett Bay watershed.

Hypoxic events in Greenwich Bay also follow trends based on freshwater river flow as river flow often acts as a vector for nonpoint sources of pollution, as well as impacting the stratification and flushing rates of the area. It is cited that an increase in river flow is linked to high nitrogen load, severe hypoxia, strong stratification and finally a major influence on flushing rate (Codiga, et al, 2020). The first Pearson correlation test that was conducted to determine the association between river flow and the water quality of Greenwich Bay was monthly average river flow versus monthly average near bottom dissolved oxygen concentrations at the Greenwich Bay sampling location. This analysis concluded that there was a weak positive association between the two variables; this states that as river flow increased so did the near bottom concentration of dissolved oxygen. I believe that increased river flow causes a short-term increase in near bottom dissolved oxygen because of increased rates of flushing that cause higher amounts of aeration and mixing to occur. This second Pearson correlation determined the association between yearly average Hunt River flow and the yearly average number of hypoxic days again at the Greenwich Bay sampling location. Another Pearson correlation analysis was conducted utilizing the data collected from the Sally Rock Sampling with the same variables, this test concluded statistically insignificant findings with little to no correlation between the two variables. This proves that river flow disproportionately affects different geographic locations within Greenwich Bay, with the Sally Rock sampling location being impacted less than the Greenwich Bay sampling location. This short-term improvement in water quality at the Greenwich Bay sampling location is outweighed by the fact that there is a moderate positive association between an increase in yearly average Hunt River flow and an increase in the yearly average number of hypoxic days. This entails that as Hunt River flow increases so does the number of hypoxic days experienced at the Greenwich Bay sampling location. This contradicts the short term increases in near bottom dissolved oxygen experienced at the monthly scale with an overall decrease in near bottom dissolved oxygen experienced at the yearly scale. This Pearson correlation was conducted utilizing data from the Sally Rock sampling location, and it proved statistically insignificant results with little to no association between variables. This highlights that hypoxia in Greenwich Bay is highly localized and different environmental factors like river flow impact the water quality of Greenwich Bay differently depending on the geographic location.

This localization in hypoxic events could be caused by the greater depth at the Sally Rock sampling site. The Greenwich Bay sampling location has surface samples taken at an average of .5 meters, and bottom samples taken at an average of 2 meters. Meanwhile at the Sally Rock sampling site, surface samples are taken at an average .5 meters and bottom samples taken at an average of 4 meters. This 2-meter difference in near bottom samples could be a factor in why the Sally Rock sampling location was impacted differently by precipitation and river flow, as well as an overall smaller number of hypoxic days. Overall, the Sally Rock sampling location is not impacted by river flow as much as the Greenwich Bay sampling site is. These findings prove that freshwater river flow from tributaries in Greenwich Bay play a role in the creation of hypoxic conditions especially at the Greenwich Bay sampling location which is in closer proximity to a source of freshwater river flow.

Policy alternatives:

Based on the results provided above, a series of policy alternatives can be created to improve current water quality conditions of Greenwich Bay as well as create alternatives that lead to the long term and gradual improvement of water quality conditions. Policy alternatives can be organized into ideas that reduce the amount of nutrients like nitrogen and phosphorus from entering Greenwich Bay, and secondly ideas that aim to reduce both the amount of fecal coliform, as well as nutrients that enter the Greenwich Bay watershed. These two pollutants are deemed the two most detrimental anthropogenic impacts to Greenwich Bay which is why policy alternatives should focus on these two pollutants. Both pollutants are examples of nonpoint sources of pollution as they are carried through untreated stormwater runoff and freshwater river flow from tributaries within the Greenwich Bay watershed. This makes management of these pollutants difficult as there is no one area in which these pollutants are entering Greenwich Bay. This leads to some areas of Greenwich Bay being disproportionately affected by anthropogenic change such as beach closures, or hypoxic events.

Excessive nutrients enter the Greenwich Bay watershed by fertilizers used in personal homes which is exacerbated through overdevelopment of green spaces, and through WWTF effluent. Excess nitrogen enters the watershed through point sources of pollution as through WWTF effluent, and in nonpoint sources of pollution through stormwater and groundwater runoff. Both sources are common in suburban and urban areas, as in the Town of East Greenwich and the City of Warwick. The frequency of stormwater outfalls surrounding the Northern embayments as seen in figure 5 depicts the number of outfall locations within the coastal areas of Greenwich Bay. To limit the introduction of excessive nutrients into Greenwich Bay, the use of fertilizers in both the personal and commercial sense should be limited, especially between the months of May to October when hypoxia is most common in the Greenwich Bay watershed. As previously determined the northern embayments of Greenwich Bay are the most susceptible to higher concentrations of specific pollutants, which is why coastal areas surrounding these embayments should have stricter restrictions on the quantity of fertilizer that can be used as well as when fertilizers can be used. An extensive investigation of nitrogen budgets within the Greenwich Bay watershed was conducted by Urish and Gomez with the Department of Civil and Environmental Engineering at the University of Rhode Island in 1998. This nitrogen budget analysis provided information regarding personal fertilizer usage within the Greenwich Bay watershed. Based on average lawn size estimation as well as application rates, the researchers found that fertilizer application rates range from 1 kg per year to 1.4 kg per year (2.2 pounds to 3 pounds per year) (Urish, Gomez, 1998). These researchers also estimated that within the municipalities of Warwick, West Warwick, and East Greenwich 50% of homes utilized fertilizers. Finally, based on uptake from vegetative zones in the soil it was estimated that only 25% of the fertilizer is estimated to reach groundwater (Eichner, Cambareri, 1991). Based on these estimations it is believed that 2.3 kg (5 pounds) of nitrogen reach Greenwich Bay from fertilizer use per day; it was determined that personal fertilizer use was the second largest source of nitrogen into Greenwich Bay based on this budget analysis (Urish, Gomez, 1998). Researchers were also able to determine nitrogen loading into Greenwich Bay based on sub basins which highlight areas of highest concern as well as which areas utilize the largest number of fertilizers. The three sub basins with the highest contributions of nutrients due to fertilizer use were Hardig Brook, the Maskerchugg River, and Tuscatucket Brook. These sub basins contributed in order 12,988, 7,386, and 6,780 grams per day of nitrogen loading per year (Urish, Gomez, 1998). Hardig Brook flows directly into Apponaug Cove, The Maskerchugg River flows into Greenwich Cove, and finally Tuscatucket Brook flows into Brushneck and Buttonwoods Coves. Two out of three of these sub basins flow into the northern embayments of Greenwich Bay further highlighting the need for more strict regulations when it comes to personal fertilizer use within the northern embayments of Greenwich Bay. The Rhode Island Department of Environmental Management (RI DEM) has provided a series of recommendations regarding the most appropriate times and quantities of fertilizers to be used but these recommendations do not hold effective regulatory power. These recommendations include, forgoing the use of fertilizers all together by using natural grass clippings as a source of nutrients, if fertilization is desired then fertilizing in September is the most optimal month to do so, asking your lawn care company about their environmental conscious options when it comes to fertilizer quantities and application timeframes, avoiding using fertilizers or pesticides near wetlands or within 75 feet of waterways, and finally checking the weather forecast before applying any fertilizers to ensure it will not rain immediately after applying fertilizers which will runoff before they have the chance to penetrate into the soil (RIDEM, 2022). The recommendations focus on limiting the quantity of fertilizers used within personal lawns, especially in coastal areas as well as near waterways. These recommendations made by the RIDEM should be adopted into local municipal regulations, especially in areas surrounding Apponaug, Brushneck, Buttonwoods, Warwick, and Greenwich Coves and their associated tributaries that all deposit into Greenwich Bay. By specifically targeting these municipalities that directly border these embayment's, there would be a decrease in the amount of excessive nutrients that are carried by untreated stormwater runoff and through freshwater river flow into Greenwich Bay.

Another policy alternative regarding limiting or reducing the amount of nutrients that enter Greenwich Bay is more upgrades to the East Greenwich Wastewater Treatment Facility (WWTF). Technological upgrades to WWTF equipment are a proactive and long-term solution to allow treatment facilities to better treat effluent entering Greenwich Bay. Management policies and significant investments into WWTF across all Narragansett Bay have proved to be an effective method of reducing nitrogen flux, especially since the early 2000s (Narragansett Bay Estuary Program, 2017). Nitrogen budgets from 2000 to 2004 and 2013 to 2015 revealed a 55% decrease in WWTF loadings of total nitrogen throughout the entire Narragansett Bay watershed, this was also evident by a 62% decline in total nitrogen loadings from river sources (Narragansett Bay Estuary Program, 2017). Looking even further back, since the early 1980s to 2017 total nitrogen loadings to the Narragansett Bay Watershed have decreased by 55% (Narragansett Bay Estuary Program, 2017). Examples of nitrogen reductions in both Greenwich Bay and Narragansett Bay are evident in figure 7 which highlights a decrease in the number of hypoxic days experienced at two different sampling locations in Greenwich Bay. This reduction in the number of hypoxic days over time after treatment facility upgrades are a clear example of why equipment upgrades are an effective management tool when it comes to reducing the amount of nutrients that enter Greenwich Bay. Based on studies conducted by the Rhode Island Department of Environmental Management (RI DEM) implementation of WWTF improvements that maximize nutrient removal would initially reduce the summer season nitrogen load discharged from WWTFs by 65%, then dropping to 48% as WWTF flows increase to their approved design flow. These studies particularly pertain to WWTFs within Rhode Island that discharge effluent into the Upper Bay region of Narragansett Bay which includes Greenwich Bay (Rhode Island Department of Environmental Management, 2005). The East Greenwich WWTF discharges into the northern reaches of Greenwich Cove, which is a shallow, poorly flushed area that exacerbates the impact of eutrophication caused by an influx of nutrients derived from WWTF effluent. The location of the East Greenwich WWTF and discharge location are why past and present efforts to reduce nitrogen discharges into Greenwich Bay have been principally focused on WWTF upgrades (Rhode Island Department of Environmental Management, 2005). For this reason, further nutrients through WWTF upgrades should continue as completed in the past to ensure the East Greenwich WWTF contributes the smallest amount of nitrogen into Greenwich Bay possible.

A policy alternative surrounding both nutrient reductions as well as reducing the introduction of fecal coliform in Greenwich Bay is through the preservation of undeveloped land which is also known as green space. Developed land is often measured by the amount or percent coverage of impervious surfaces within a designated area. As determined by literature surrounding Greenwich Bay, increasing coverage of impervious surfaces is linked to higher concentrations of nonpoint sources of pollution in Greenwich Bay, nitrogen, and fecal coliform being two of those pollutants. Researchers have determined that stormwater generated on developed land is considered a point source while stormwater on undeveloped or green spaces is a nonpoint source. Based on the Rhode Island Department of Environmental Managements Total Maximum Daily Load (RIDEM TMDL) it is determined that two thirds of the required fecal coliform reductions come from point sources while the remaining one third of reductions come from nonpoint sources of pollution (RIDEM, 2005) Developed lands are a major source of bacteria in the watershed; undeveloped land therefore needs to be protected especially in coastal areas, and areas near tributaries. One counter argument to the preservation of undeveloped green spaces is that greenspaces are oftentimes converted into areas like parks and natural spaces for the public to use for recreation. Increasing the area of greenspaces will come with a larger population of people who will use those areas for recreational purposes which often includes dogs. Some believe that increased populations using green spaces will contribute to increased concentrations of bacteria, especially fecal coliform even when people pick up after their dogs. Pollution prevention efforts are recommended to counter the negative effects of increased populations using green spaces. These measures include discouraging residents from feeding birds and to encourage residents to pick up after their pets (RIDEM, 2005). Furthermore, it is recommended that residents receive educational material about measures they can take to minimize and prevent their contribution to water quality degradation issues. Tactics include posting signs that educate residents about the importance of properly disposing of their pets' waste and designating areas with pet waste bags and containers (RIDEM, 2005). These educational measures are a productive way to extend awareness about these issues as well as keep green spaces as areas that can slow down stormwater runoff from impervious surfaces. Coastal land, and land surrounding rivers and tributaries especially around Apponaug, Buttonwoods, Brushneck, and Warwick coves in the northern reaches of Greenwich Bay should be areas in which green space should be protected.

Climate change is an ever-looming threat to coastal ecosystems as well as stakeholders and residents that live and interact with marine spaces. A passive benefit of green spaces and the protection of undeveloped land in the Greenwich Bay watershed is the protection these areas provide during increased flooding and overall sea level rise.

While this study utilized a small-time scale in terms of much larger climatological changes and patterns the effects of our changing climate cannot be ignored. Locally in Rhode Island, sea level rose nine inches from 1930 to 2015 based on measurements taken from a gauge in Newport which is in the southern extent of the state. In Providence, which is located north of Greenwich Bay, sea level rose 6.6 inches from 1938 to 2015 (Narragansett Bay Estuary Program, 2017). Future estimations from the National Oceanic and Atmospheric Administration (NOAA) state that sea levels in Newport Rhode Island could rise as much as 3.4 feet by 2050 and 11 feet by 2100 (Narragansett Bay Estuary Program, 2017). This evidence of sea level rise overtime brings up concerns related to developed land along our coastline and the potential issues that could be experienced especially during storm events. According to sea level rise estimates approximately 17 square miles of land within the Narragansett Bay coastline and 3,765 buildings would be inundated under a seven-foot sea level rise scenario (Narragansett Bay Estuary Program, 2017). The preservation of greenspace as a buffer in coastal areas including the Greenwich Bay watershed is an effective strategy to limit the amount of flooding caused by rising sea levels especially during major storm events. Greenspaces and undeveloped lands in the Greenwich Bay watershed are an effective policy alternative that targets a variety of environmental issues such as the slowdown of nonpoint sources of pollution such as bacteria and nitrogen, as well as protecting businesses and homes from rising sea levels and flood events.

According to the Rhode Island Department of Environmental Managements Total Maximum Daily Load Analysis (RI DEM TMDL) Best Management Practices or BMPs are specifically a set of management efforts that target new construction efforts and the development of land in the Greenwich Bay watershed. The six minimum control measures in which BMPs fall under are scheduled activities, prohibitions, maintenance, and other management practices that prevent or reduce the pollution and impacts upon waters of the state. BMPs also include treatment requirements, operating procedures, and practices to control the introduction of pollutants into a waterbody (RIDEM, 2005). BMPs therefore are of particular interest for this study when it comes to policy alternatives surrounding the preservation of undeveloped land and limiting the use of fertilizers, especially when it comes to golf courses. BMPs directly impact different land use practices in the Greenwich Bay watershed, these being how new development and redevelopment efforts are completed, and the construction of different stormwater volume reduction methods. New development in the Greenwich Bay watershed must follow these listed BMPs within RIDEMs TMDL document to prevent or reduce the pollution of and impacts upon waters of the State. According to the RIDEM recommendations surrounding BMPs include stormwater retrofit activities at state and locally owned stormwater outfalls. This recommendation is important when it comes to reducing the amount of polluted stormwater that enters Greenwich Bay; it does not remove sources of pollutants which continue to pollute through surface runoff. The policy alternatives in this study particularly aim to track sources of pollutants in the watershed and implement changes that tackle pollutants at the source. New construction efforts need to aim towards reducing impervious surfaces, sloping impervious surfaces to drain towards vegetated areas, using porous pavement, and installing infiltration catch basins where feasible; these BMPs are utilized to reduce runoff volumes and at times treat stormwater (RIDEM, 2005). An extension of BMPs relation to development in the Greenwich Bay water is through two out of the six minimum control measures. These two measures being a construction site stormwater runoff control program for sites disturbing one or more acres, and second being a post construction stormwater runoff control program for new development and redevelopment sites disturbing one or more acres (RIDEM, 2005). Finally, BMPs specifically related to fertilization in the watershed include the use of controlled release fertilizers, the use of bent grass and lower irrigation rates. These efforts limit nutrient loss from golf courses therefore limiting the amount of nitrogen in nonpoint sources of pollution like stormwater runoff. The RIDEMs TMDL document establishes areas of highest concern when it comes to fecal coliform as well as where BMPs should be prioritized to combat these areas of highest concern. BMP construction within the City of Warwick should be prioritized on the land surrounding Brushneck Cove, Apponaug Cove, and its headwaters of Hardig Brook. (RIDEM, 2005). These two northern embayments have the highest concentration of fecal coliforms which was determined by the RIDEM in their 2005 TMDL document and is still consistent today with these northern embayments having the highest concentrations of fecal coliform determined in this study. As for the Town of East Greenwich, Greenwich Cove is the area of highest concern in which BMPs should be prioritized. Three out of the six minimum control measures have BMPs that are centered around reducing the amount of nutrients, and fecal coliform that enter Greenwich Bay. These three minimum control measures are: the formation of a construction site stormwater runoff control program for sites disturbing one or more acres, a postproduction stormwater runoff control program for new development and redevelopment sites disturbing one or more acres, and finally a municipal pollution prevention or good housekeeping operation and maintenance program. Oftentimes the construction and post construction minimum control measures are joined together, and solutions are centered around stormwater volume reduction measures. These requirements are for development and redevelopment of commercial and industrial properties. To comply with the construction and post construction minimum measures, acceptable reduction measures include reducing impervious surfaces, sloping impervious surfaces to drain towards vegetated areas, using porous pavement, and installing infiltration catch basins where feasible (RIDEM, 2005). The final minimum control measure includes BMPs surrounding municipal pollution prevention as well as good housekeeping operation and maintenance-based solutions. These BMPs are very similar to previously mentioned solutions but this minimum control measure also includes that any new municipal construction or retrofit project should incorporate BMPs that reduce the quantity of stormwater and promote infiltration. This can be achieved with the installation or creation of buffer strips, swales, vegetated drainage ways, infiltrating catch basins, or roads made from porous materials (RIDEM, 2005). These BMPs should continue to be worked into any retrofit or new construction activities that occur within coastal lands or lands within proximity to rivers and tributaries that discharge into Greenwich Bay.

Individual sewage disposal systems (ISDS) also known as Onsite Wastewater Treatment Systems (OWTS), septic systems and on-site wastewater systems are essentially all the same kind of wastewater treatment system that does not rely on municipal sewers or treatment facilities. Another policy alternative that needs to continue in the Greenwich Bay watershed is the elimination of these ISD systems to mitigate the introduction of both nitrogen and fecal coliform into Greenwich Bay waters. In both the municipalities of East Greenwich and Warwick there are mandates surrounding the tie-in of residential properties to municipal sewer lines if sewer lines are available in the area. These mandates particularly apply to any new construction efforts, in which all newly constructed homes need to tie into municipal sewer lines. ISD systems need to be tied into either municipal sewer systems to ensure proper treatment of wastewater is achieved. ISD systems were very common in the Greenwich Bay watershed throughout history, but as municipal sewer systems and treatment facilities became more viable, it was clear that these systems were far better than ISD systems. Overtime ISD systems are prone to failures which result in the leakage of untreated sewage into groundwater, into tributaries, or directly into surface waters of Greenwich Bay. Properly functioning ISD systems, and especially failing ISD systems are known to leach high amounts of nitrogen which often do not get treated before reaching Greenwich Bay (RIDEM, 2005). Researchers have further proved the negative impacts of ISD/OWTS as a source of nitrogen directly into the Hunt River which is a river adjacent to the Greenwich Bay Watershed. The use of hydrologic modeling with soil and water assessments lead researchers to determine that the total nitrogen loads in years where OWTS were considered were twice as high as those scenarios where OWTS were not included in simulations (Paul, 2017). Other studies estimated that ISD systems contribute between 47 to 57 metric tons of nitrogen per year to Greenwich Bay (RI CRMC, 2005). Additionally, with a decrease of 21,000 people being serviced by ISD systems it could eliminate more than 56% of the overall nitrogen input into Greenwich Bay (RI CRMC, 2005). ISD systems and cesspools are two of the largest contributing sources of fecal coliform into Greenwich Bay, stormwater carries bacteria from both sources into both tributaries as well as directly into Greenwich Bay (RI CRMC, 2005). Additionally, due to both wet and dry weather exceedances of fecal coliform concentrations in areas like Appanoug cove, failing ISD systems that leach untreated sewage into groundwater are believed to be the cause of dry weather fecal coliform exceedances. Over the past 20 years there have been planned sewer extensions within both Warwick and Greenwich Bay, these sewer extensions allow homes that have ISD systems to tie into WWTF and remove their outdated and substandard method of wastewater treatment. Warwick has spent more than $50 million in expanding sewer lines in the Greenwich Bay watershed and the Coastal Resource Management Council (CRMC) has required the city of Warwick to adopt a mandatory tie-in schedule for residential and commercial areas that drain to Greenwich Bay, which has been successfully adopted. The CRMC has also determined that areas of highest concern are areas surrounding Brushneck, and Apponaug Coves, this is consistent with the findings determined in this paper (RIDEM, 2005). Based on fecal coliform findings in tables 2 .055% of total fecal coliform data was over the threshold for safe swimming across all of Greenwich Bay. As for shellfishing depicted in table 3 5.01% of total fecal coliform data was over the threshold for safe shellfishing across all of Greenwich Bay. Due to the threshold for safe being much more stringent than the threshold for safe swimming at 50 cfu/100ml rather than 14 cfu/100 ml for shellfishing. As policy alternatives like the tie in of ISDS occur in the watershed there will be less beach closures and impacts to tourists overtime. Through fecal coliform reductions I expect beach closure events to become rarer before shellfishing becomes viable in the 5 shallow embayments which are permanently closed for shellfishing. Beach sand recreational areas around the watershed should continue to be monitored for bacteria like fecal coliform to evaluate fecal coliform reductions overtime. Mandatory sewer tie-ins and sewer extensions should be continued until all ISD systems within the Greenwich Bay watershed are removed in the case where homes can be tied into WWTF. In areas where sewer lines have not been extended there should be ordinances with an enforceable mechanism to ensure that existing septic systems are properly operating and maintained. Areas of highest concern should be eliminating ISDS in remaining homes within proximity to Brushneck Cove, and Potowomut, this can be achieved through the continuation of sewer extension projects. These efforts need to continue until there is a complete elimination of ISD systems within the Greenwich Bay watershed to negate the introduction of excessive nitrogen and fecal coliform into Greenwich Bay.

CHAPTER 5

CONCLUSIONS

The Greenwich Bay watershed suffers from hypoxic conditions as well as elevated levels of fecal coliform, this is reflected by negative impacts caused to both the ecology and stakeholders of Greenwich Bay. Shellfish closures, beach closures, and fish kill events are some of the clearest examples that the water quality of Greenwich Bay is severely impacted by the urbanization of East Greenwich and Warwick. Ambient water quality trends as well as specific pollutant monitoring efforts reflect these trends by highlighting the northern embayments as areas of highest concern. Analyzing these data sources highlights how precipitation can act as a forcing factor for hypoxic conditions. The analysis of ambient water quality and pollutant monitoring data has determined that excessive nutrients like nitrogen and fecal coliform are the two most impactful pollutants in the Greenwich Bay watershed. Both ambient water quality monitoring and specific pollutant monitoring efforts show gradual water quality improvements overtime which shows the effectiveness of past management efforts regarding mitigating the introduction of pollutants in the watershed. Future policy alternatives are recommended due to poor water quality which hinders stakeholders like tourists and fishermen from utilizing Greenwich Bay. These alternatives should be adopted to specifically combat fluxes of nitrogen and fecal coliform into the watershed.

Future efforts should be directed towards the complete elimination of ISDS, OWTS, septic, and cesspools in both East Greenwich and Warwick. This goal can only be achieved with the completion of sewer extension projects within the watershed, this includes areas like the Pottowomut community which have had previous issues with sewer extensions due to the presence of bedrock in the area. Another improvement to be made is surrounding further enforcement of mandatory sewer tie-ins, as there are examples of homes in both East Greenwich and Warwick that have access to sewer extensions but have not tied in yet. Improved enforcement measures are crucial as sewer extension projects are completed and new homes become available to sewer lines. Furthermore, improved enforcement measures are a sound method to eliminate remaining OWTS within the Greenwich Bay watershed. In terms of further research efforts, current water quality conditions need to be accurately reflected in regulatory documents such as TMDL calculations, SAMP documents, and nitrogen loading estimations into Greenwich Bay. Previous TMDL calculations were completed in 2005 and only conducted for fecal coliform with little effort surrounding nutrients like nitrogen. New TMDL calculations should be conducted using updated data from 2005 to 2024 for both fecal coliform and nitrogen. The most recent SAMP conducted by the RI CRMC was also in 2005. Like TMDL calculations, updated water quality data and stormwater management efforts should be reflected in a new and improved SAMP. Finally, nitrogen budgets were completed for Greenwich Bay in the late 1990s, current nitrogen budgets should be recompleted to better reflect conditions in the watershed and give researchers the ability to evaluate past nitrogen reduction efforts. Updated nitrogen budgets would also allow for more informed decision making in terms of nitrogen reductions. Through the course of this study, future research should focus on conducting pollutant monitoring and ambient water quality monitoring around stormwater outfall locations in Greenwich Bay. There is a severe lack of monitoring effort at these outfall locations which make determining the source of nonpoint sources of pollution even more difficult. Impaired waterways like Greenwich Bay, especially ones with TMDL calculations should have mandatory monitoring efforts at outfall locations. Pollutant monitoring of stormwater outfalls should especially occur in the northern embayments of Greenwich Bay which have been established as areas of highest concern within this study. Another data gap that needs to be further investigated is the lack of river flow data from the tributaries that discharge into Greenwich Bay. Tributaries like Hardig Brook, Tuscatucket Brook, and the Maskerchugg River do not have any long term or consistent flow rates. This made determining the effect of freshwater river flow into Greenwich Bay extremely difficult and this data would be extremely useful in accurately understanding how river flow impacts the water quality of Greenwich Bay. This study aimed to utilize ambient water quality data and specific pollutant monitoring efforts conducted by a variety of different Rhode Island agencies to create a series of policy alternatives. It is my goal to create a series of policy alternatives which drive scientifically informed decision making and lead to effective management that improves the water quality of Greenwich Bay.

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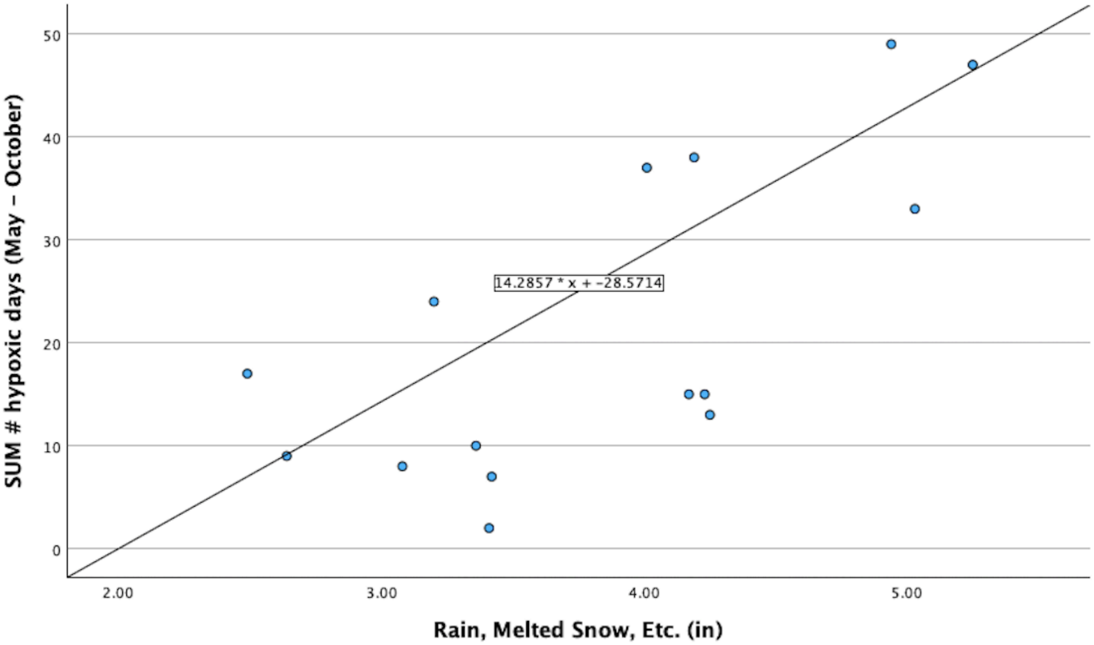
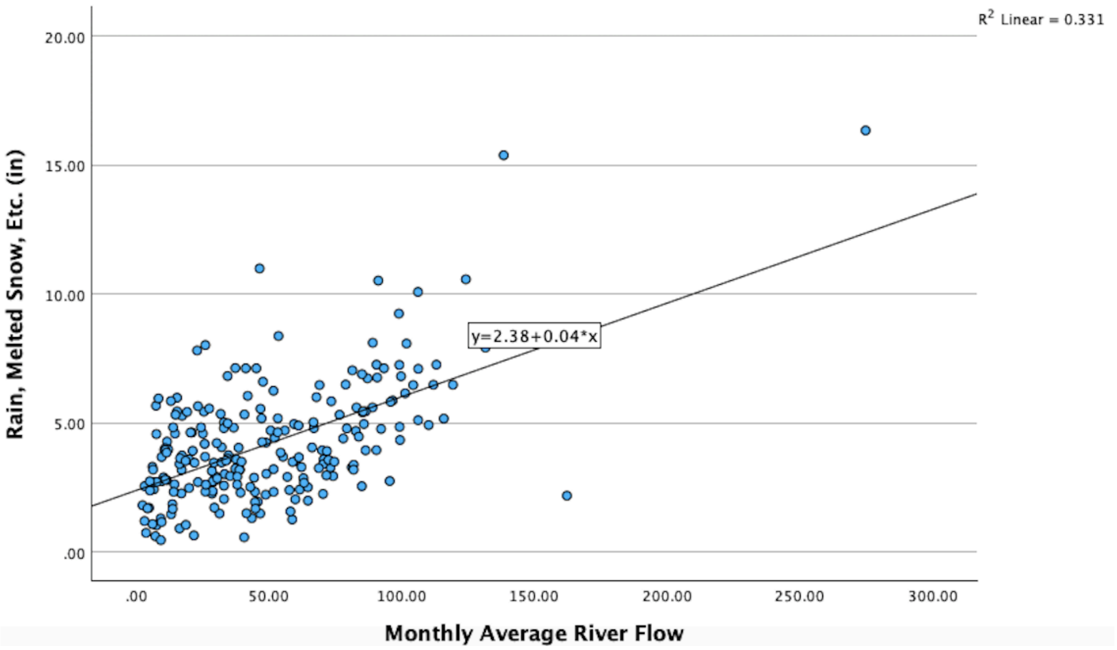


Appendix Figure 1: Average precipitation compared to hypoxia

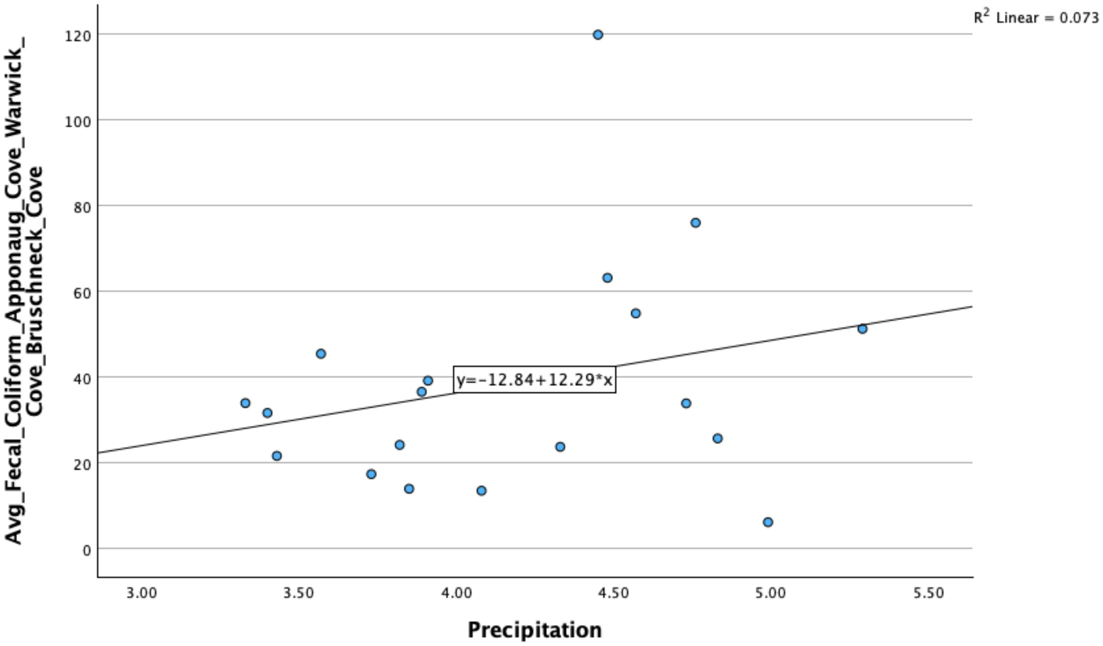
Yearly average precipitation measured in inches at the T.F. Green International Airport is plotted against the number of hypoxic days at Sally Rock sampling location.

Figure is further supported by a strong positive correlation between the variables indicating as precipitation increases so do the number of hypoxic days. Data sources: Narragansett Bay Fixed-Site Monitoring Network (NBFSMN) and NOAA National Centers for Environmental Information for precipitation measurements.



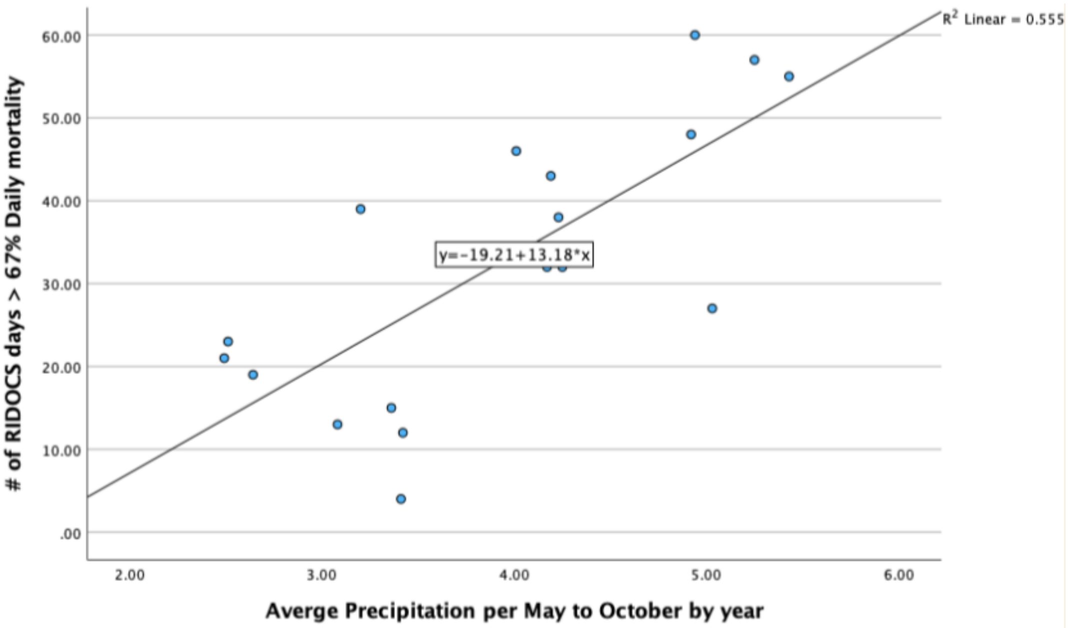
Appendix Figure 2: Average river flow compared to average precipitation

Monthly average Hunt River flow in cubic feet per second plotted against monthly average precipitation measured in inches at the T.F. Green International Airport. Data range covers 2005 to 2022. Data source: U.S. Geological Survey (USGS) for Hunt River flow data and NOAA National Centers for Environmental Information for precipitation measurements.



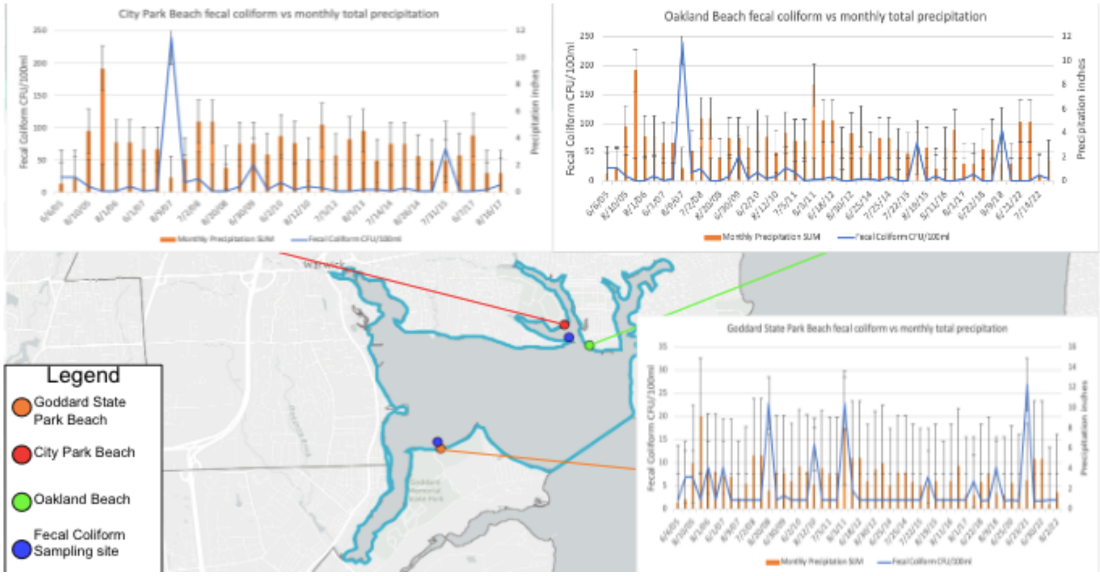
Appendix Figure 3: Average precipitation compared to average fecal coliform at areas of highest concern.

Yearly average precipitation measured in inches at the T.F. Green International Airport vs yearly average fecal coliform value in cfu/100 ml for the three sites with the highest concentrations of fecal coliform, those being sites in Apponaug, Brushneck, and Warwick Coves. This data covers the date range of 2005 to 2022. Minimal slope in line of best fit signifies that precipitation does not influence the concentration of fecal coliform. Data sources: NOAA National Centers for Environmental Information, and RI DEM, Office of Water Resources, Shellfish Water Quality Program for fecal coliform data.



Appendix Figure 4: Average total precipitation compared to hypoxic days

Yearly average total precipitation at Green Airport in inches vs number of hypoxic days at the Greenwich Bay sampling location. This data exclusively utilizes data from the months of May - October to calculate yearly averages, these are the months in which hypoxia is most common. This data covers the date range of May 2005 to October 2022. Data source: NOAA National Centers for Environmental Information for precipitation measurements, and Narragansett Bay Fixed-Site Monitoring Network (NBFSMN) for hypoxic days dataset.



Appendix Figure 5: Fecal coliform measurements at points of beach closures

Fecal coliform measures during the months of June to August during years when beach closures occur. Beach closures at these three beaches are based on individual bacteria sampling efforts conducted by the Rhode Island Department of Health which is not utilized in this study. Precipitation does not appear to have a visual relationship with the concentration of fecal coliform found at any of sampling sites. The highest concentrations of fecal coliform do not consistently occur when precipitation increases. Data sources: RI DEM, Office of Water Resources, Shellfish Water Quality Program, and NOAA National Centers for Environmental Information.

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